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Some Aspects of Growth, Recruitment and Reproduction in the Southern Saucer Scallop, *Amusium balloti* (Bernardi, 1861) in Shark Bay, Western Australia

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WESTERN AUSTRALIAN
MARINE RESEARCH LABORATORIES
DEPARTMENT OF FISHERIES AND WILDLIFE
PERTH, WESTERN AUSTRALIA

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SOME ASPECTS OF GROWTH, RECRUITMENT AND REPRODUCTION IN THE SOUTHERN SAUCER SCALLOP, *Amusium balloti*, (BERNARDI, 1861) IN SHARK BAY, WESTERN AUSTRALIA

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ABSTRACT

Growth, recruitment and reproduction were investigated in a Shark Bay, W.A., population of the scallop, *Amusium balloti* (Bernardi). Height frequency data showed that *Amusium* has a life expectancy of less than 3 years from larval settlement. Growth between 1+ and 2+ years is marked by strong seasonality—fast growth in "summer (October–March) and slow growth in the balance of the year. Growth rate of 0+ and 1+ scallops averages 5·5 mm per month but declines in 2+ scallops to 3·6 mm per month. A von Bertalanffy curve $H_t = 103 \cdot 85\{1 - e^{-1 \cdot 4162 (t - 0.356)}\}$ provided an adequate description of average growth based on tag recaptures, but improved prediction of height at age could be obtained from a seasonally adjusted equation. Good agreement was obtained between growth rates calculated from height frequency and from tag recapture data. The relative numbers of the 1+ and 2+ year classes which varied markedly with area, were thought to reflect different patterns of year class settlement in areas not fished in the previous season. Scallops of 1+ and 2+ age are fully retained in prawn or scallop mesh nets, but only 2+ scallops are saved because of the processors minimum shell size requirement. Recruitment of the 1+ year class to commercial size may vary from March to September in different years. The 0+ class is not readily caught because of its small shell size. The analysis of effect of depth on mean shell height proved indeterminate. First spawning occurs at approximately one year of age, in early summer. No significant difference was detected between the sexes in mean shell height at age or their proportions in the population.

I INTRODUCTION

The southern saucer scallop *Amusium balloti* is one of the few bivalve molluscs to have obtained commercial significance in Western Australian waters. Its presence has been known in W.A. since 1904, when it was first reported in survey catches by the ketch "Rip" (Gale 1905). An *Amusium* fishery in Shark Bay subsequently began in 1966 with a landing of 5·8 tonnes live weight. Since then, *Amusium* has supported a fishery in Shark Bay based on catches of up to 11 full time scallop trawlers each year and subsidiary catches of scallops by prawn trawlers. With the exception of the years 1967 and 1971 when stocks fell below commercial density, landings have fluctuated between 5·8 and 1 400 tonnes live weight.

Sporadic landings from the Abrolhos Islands and waters near Rottnest Island have also been made, these latter grounds having a much smaller total area in which commercial densities of scallops are commonly found. Figure 1 shows the areas where commercial landings of southern saucer scallops have been made and areas of known occurrence.

When the need for conservation and rational management in a fishery becomes evident, any decisions to regulate the catches of a stock are usually based on yield predictions which in turn presuppose a knowledge of the growth coefficient K, the natural mortality M, and the fishing mortality F. The optimum yield from a single species fishery is dependent on the growth rate attained and the size at first capture (Beverton and Holt 1957). The purpose of this paper therefore is to present an analysis of growth based on tagging and height frequency data in *Amusium balloti* which is seen as a first step towards estimating the parameters of Beverton and Holt's yield equation to allow for future rational management of the *Amusium* fishery in W.A. Several methods for determining K and age composition of scallops have been discussed in the literature. They can be divided into those methods which require either an assessment of the age of the scallops or the separation of size frequency data into age classes, and those which are based on tagging or cage studies where growth can be measured directly.

Examples of the first group of methods include interpretation of growth rings on the valves of *Pecten maximus* (Mason 1957; Baird 1966), *Patinopecten yessoensis* (Maru and Obara 1965), *Placopecten magellanicus* (Stevenson and Dickie 1954; Merril, Posgay and Nichy 1966), *Chlamys opercularis* (Aravindakshan 1955) and an analysis of growth checks in the resilium of *Placopecten magellanicus* (Merril *et al* 1966). The use of size frequency distributions to determine age and growth rate such as in studies by Gutsell (1930) and Marshall (1960) on *Argopecten irradians* and by Roe, Cummins and Bullis (1971) on *Argopecten gibbus* also belong to the first group of methods. They may be perfectly satisfactory for short lived species with visibly distinct year classes, but in medium to long lived species exhibiting a large number of year classes with considerable overlap, this method is rarely sufficient for reliable assessment, due to its subjectivity.

Among the second group of methods for age and growth analysis in scallops is the technique of tagging, e.g. with Petersen discs on *Placopecten* (Posgay 1963), or celluloid discs stuck on to *Pecten medius* with gutta percha, (Tubb 1946). Tagging has also been used effectively to assess growth in *Pecten maximus* (Gibson 1953) and on most other commercially exploited species of scallops, usually with reasonable success. Scallops held under controlled or monitored conditions may also provide reliable growth data, e.g. Duggan (1973) followed the growth of aquarium held *Argopecten irradians* and Broom and Mason (1978) undertook estuarine cage studies on *Chlamys opercularis* to confirm the widely held assumption that growth checks in the valves were really annual.

Attempts to age *Amusium* valves however have proved unsuccessful to date because growth checks are not obvious on the valves. Fortunately, *Amusium* is well suited to the use of height frequency data to determine size at age, because it is short lived and has few age classes. If overlap occurs, the distributions can be reliably separated. The results obtained can be compared with a separate analysis of growth from a tagging programme, and the influences of season, depth and the reproductive cycle on growth rate can be examined.

In the present study, insufficient series of data from different areas were available to gauge if area exerted an effect on growth rate. Various height-weight, and weight-recovery equations are presented, with the seasonal effect also being considered. The growth data from recaptured tags has been fitted to a von Bertalanffy growth curve. This enables prediction of average height at age, but the raw data will intersect with the fitted curve only once per year (Pitcher and Macdonald 1973) because of the seasonal effect, which exerts a considerable influence on *Amusium* growth above 0+ years of age. To illustrate this effect, seasonal changes in the parameters of the von Bertalanffy equation have been taken into consideration.

II METHODS

A. Height frequency data

The dimensions of a southern saucer scallop are shown in Figure 2. Shell height was the parameter measured to study growth and compare samples. Height frequency samples were provided either from prawn trawlers (44/51 mm mesh nets) or scallop trawlers (102 mm mesh nets). Samples from these vessels could also differ due to the practice or not of hand culling of scallops below 89 mm shell height, depending on whether the 40 kg bag of scallops was from the commercial catch of a vessel landing scallops for processing or was obtained with special instructions to the skipper and crew to provide an unculled sample for research purposes. Some samples were also provided by the Fisheries Research Vessel "Flinders" using a 44 mm mesh net, and by various Fisheries and Wildlife patrol vessels using a try-net of the same mesh size. No samples used in the analyses which follow have been culled for any purpose. The mesh selection effect in samples from scallop trawlers made comparison with samples from prawn trawlers for the 0+ year class unreliable so the former have not been used in this case. However, a comparison of samples from these two sources was possible when only 1+ and older scallops were present. Samples from prawn mesh nets therefore proved to be the most useful for comparison since they sampled all age classes.

Most of the samples were obtained from prawn trawlers rather than Fisheries and Wildlife Department vessels. For this reason the same area could not always be sampled each month because of the fleet's requirement to change to areas of highest prawn catch rates. In addition samples were rarely available from November to January because this corresponds to a period of much reduced trawling in Shark Bay.

The data are presented as percentage frequency histograms. Scallops were measured to the nearest mm below using a pistol grip rock lobster carapace gauge and the measurements grouped into 2 mm class intervals. This choice of grouping produced some smoothing of the data without losing the 2+ mode which occurred when smaller numbers of these scallops were present in bimodal samples and the 5 mm grouping was used (Figure 3).

When the age classes overlapped in the height frequency data, they were separated using Cassie's probability paper method (Cassie 1950) or the computer programme "NORMSEP" (Abramson 1971). Height frequency distributions were examined for an indication of seasonality of growth by progression of the mode in 1+ and 2+ year classes. Regular monthly subsamples were examined for reproductive stage adapted from Harrison's criteria to determine the size of first maturity and the spawning period (Harrison 1961, see Appendix I for method). The relative proportions of 1+ and 2+ year classes were obtained using "NORMSEP", to examine the effect of area on the pattern of settlement of a year class. An attempt was made to determine the correlation between depth and average shell height of the 1+ year class using data from two separate periods. Height composition data were also examined to determine if there was a statistical difference in the height distribution of males and females of the same age. The height frequency distributions of 1+ scallops from a given fishing block were followed over a number of years to examine the development of the year classes.

B. Tagging and analyses

The principal tagging method used small plastic strip tags stuck on to the shell with alpha-cyanoacrylate cement. The same adhesive was applied to other tagging materials and other methods of tagging were also used (Heald 1978).

Liberation of tagged scallops was undertaken mainly using prawn trawlers in the oceanic waters of Shark Bay (Figure 4). Tagged scallops were also released in the waters where the Cape Peron salinocline usually establishes and in the deeper water trawling grounds adjacent to Quobba Point.

Tagging experiments were carried out between 1971 and 1974. In 1971, releases were spread evenly throughout the season from April to late October. In other years, extra tagging was undertaken to supplement recaptures from specified seasons, e.g. June to August 1972, February to March 1973 and April to May 1974. The releases which were made represent all seasons well except for the months of November to January which correspond to a period of reduced trawling activity in Shark Bay.

The analysis of growth from the tagging experiments was restricted to recaptures of scallops which had been at liberty 28 days or more because it was anticipated that scallops might require a period of re-adjustment before normal growth activity was resumed after any shock or injury sustained during the tagging process.

Of those methods of analysis available, the main method chosen to study growth of recaptured tagged scallops follows the approach described by Gulland and Holt (1959). A linear regression equation $y = a + bx$ was obtained for the tagging data where y is the rate of shell height increase $(H_2-H_1)/(t_2-t_1)$; x is the mean height at liberty $(H_1 + H_2)/2$ with H_1, t_1 and H_2, t_2 being the height and time at release and recapture respectively, and a and b the regression constants. The estimate of the growth coefficient, K, is equal to $-b$ and the estimate of H_∞, the height where the growth rate is zero, is $-a/b$.

A correction factor was used for the estimate of K from analysis of recaptures where the period at liberty was greater than 300 days. In the estimation of seasonal growth, where the period at liberty was relatively short, the correction factor was not used (Gulland and Holt 1959). The returns were separated into two categories consisting of those which had been at liberty for less than a year to provide information on seasonal growth rates and longer term recaptures, at liberty approximately 1 year, to obtain estimates of annual growth.

Recapture data from the 1971 releases have been classified into seasons according to the season in which the major part of the period at liberty was spent. The definitions below have been adopted:—

Season	*Release Month*	*Recapture Month*
Autumn	April, May	April, May, June
Winter	June, July, August	July, August, September
Spring	Sept., Oct.	October
Summer	Sept., Oct.	February, March (1972)

The summer season had to be spread over a longer period than the other seasons because of reduced trawling activity between November and January.

Manzer-Taylor plots (see Manzer and Taylor 1947) of H_{t+1} against H_t, where H_t is the shell height of an individual scallop at time t and H_{t+1} its height one year later, have been examined for recaptures at liberty approximately one year and the estimates of K and H_∞ derived in this method are compared with estimates obtained from the Gulland and Holt method using the same data.

III RESULTS

A. Height frequency data

Several hundred height frequency samples were measured from 1969–1978, but only those which were unculled were retained for comparison. Previous results by Robins (1969) indicated that 102 mm mesh scallop nets retain scallops in the size range attained at 1+ years but select against 0+ scallops in the size range 20–50 mm. Thus samples obtained from 102 mm mesh could only be compared with samples from 44 mm mesh for scallops greater than one year old.

1. *Relationship between season and growth*

In Figure 5, the series of height frequency samples from block 7807 demonstrates a period of slow growth between April 1970 (Figure 5a) and July 1970 (Figure 5f). During this period, the mode remained stationary occurring in the size classes 80–82 mm or 82–84 mm as did the mean. From July to September (Figure 5g) both the mode and mean increased by about 6 mm indicating a resumption of growth. The absence of an August 1970 sample in this series makes it difficult to state whether active shell growth actually resumed in August or September but a comparison of the modes of up to three samples in consecutive months from other fishing blocks in the same period of the year but taken in different years, indicates that the start and finish of the slow growth period varies from year to year although it generally approximates to April and August respectively.

2. *Spatial pattern of year class settlement*

The pattern of settlement for a particular year class is often quite variable. This is thought to be due to a combination of the uneven distribution of scallop larvae in the water mass after spawning and at larval settlement, and differences in mortality between year classes. The proportion of each year class can be seen in Figure 6, in which the height frequency samples a–g were from liberations of tagged scallops in 1974 in different areas. No scallop landings were taken from any of the areas sampled in Figure 6 in the previous year, so that differences in proportions shown result from natural causes. It can be seen that, in different areas, the 2+ year class may be practically absent altogether (Figure 6b), subordinate to (Figure 6d), of equal strength with (Figures 6e and 6g) or dominant to the 1+ year class (Figure 6f). The maximum separation for any two of these areas is 80 kilometres.

3. *Age structure of the population and survival of year classes*

The saucer scallop population in Shark Bay is usually dominated by one or two year classes during any given period in time (Figure 7). The year classes most commonly present are the 1+ and 2+ classes, whereas the 0+ class, when it first becomes vulnerable to capture, is quite variable in strength (compare Figure 7d with 7a, 7b or 7c). Very occasionally a sample is encountered during measurement, which from its size range (116–124 mm) is probably a 3+ year class (Figure 7i). Scallops of very large size however form such a small part of the total sample both in terms of biomass and numbers, that their relative contribution to the fishery as a component of the catch or to the total reproductive effort of the population would be negligible.

The abundance of a year class in any particular area is a function of the strength of that year class at larval settlement, and its subsequent decline due to natural mortality and fishing pressure. Unless there has been poor settlement of the 1+ class in a particular area, it is normally identifiable in samples as a 2+ class in the following year. Thus the 1+ year classes noted in Figures 8a, 8f and 8i could still be identified, noted as 2+ in Figures 8b, 8g and 8j respectively. In contrast, the 2+ class rarely survives the full 12 months of its third year to emerge as a distinct 3+ mode in height frequency samples, except possibly as already noted in Figure 7i.

4. *Average growth rate and annual growth.*

The average growth rates during the life of the different year classes (0+, 1+, 2+) can be calculated if the average size can be related to a known or estimated age. This has been done for *Amusium* (Table 1) with the assumptions that January 1st approximates the settlement of each successive year class in the Shark Bay population (see also Section 8 of Results) and that average size at age can be represented by the mode. The average growth rates to the stated ages shown, ranged from 4·0 to 7·0 mm/month for 0+ scallops with an overall mean of 5·5 mm/month (5 samples); 4·1 to 6·1 mm/month for 1+ scallops with an overall mean of 5·1 mm/month (6 samples); and 3·2 to 3·9 mm/month for 2+ scallops with an overall mean of 3·6 mm/month (5 samples). The overall means were tested by Students "*t*" and it was found that the overall mean monthly growth rate for 0+ was not significantly different from the mean rate for 1+ ($p = 0{\cdot}346$) but the rate for the latter was significantly greater than the overall mean rate for 2+ scallops ($p < 0{\cdot}01$).

Net annual growth in a population may be determined (i) by sampling at 12 month intervals, or (ii) age cohorts may be separated out from poly-modal size distributions for comparison of age related annual growth. For the *Amusium* population, the first method was of limited use and application because it was rarely possible to replicate samples from precisely the same area during the same month in consecutive years. The second method was used to obtain estimates of annual growth between

TABLE 1—A COMPARISON OF AVERAGE MODAL GROWTH RATES (mm/month) IN SCALLOP SAMPLES OF DIFFERENT ESTIMATED AGES, BASED ON A STANDARD BIRTHDATE OF JANUARY 1st. SAMPLES WERE TAKEN FROM FISHING BLOCKS SHOWN

Sample Date	Fishing Block	Estimated Age (months)	Mode (mm)	Average Shell Growth Rate (mm/month)	Year Class
9/9/1969	7806	8	56·1	7·0	0+
27/9/1971	7706	9	46·5	5·2	0+
1/11/1972	8205	10	48·5	4·9	0+
15/11/1977	7806	10·5	68·1	6·5	0+
12/12/1978	7706	11·5	46·0	4·0	0+
24/2/1969	7806	14	85·3	6·1	1+
11/9/1970	7806	20	81·4	4·1	1+
21/8/1974	7806	20	90·4	4·5	1+
5/5/1975	7806	16	82·8	5·2	1+
14/1/1977	7806	12·5	75·8	6·1	1+
19/6/1978	7806	18·5	84·8	4·6	1+
24/2/1969	7806	26	101·0	3·9	2+
11/9/1970	7806	32	101·3	3·2	2+
5/5/1975	7806	28	98·4	3·5	2+
14/1/1977	7806	24·5	97·0	3·9	2+
19/6/1978	7806	29·5	102·4	3·5	2+

TABLE 2— (a) DIFFERENCES BETWEEN THE MODES OF CONSECUTIVE YEAR CLASSES—1+ AND 2+ SAMPLED SIMULTANEOUSLY IN VARIOUS FISHING BLOCKS IN SHARK BAY, ARRANGED CHRONOLOGICALLY AND (b) DIFFERENCES IN MODAL SIZE IN FIVE DIFFERENT COHORTS MEASURED AT 1+ AND THEN AT 2+ IN VARIOUS FISHING BLOCKS AND YEARS IN SHARK BAY, FOLLOWED OVER A PERIOD OF APPROXIMATELY 1½ YEARS

(a)

Date of Sample	Fishing Block	Modal Size (mm)		12-month mode difference	Season of Sample
		1+	2+		
February, 1969	7806	85·3	101·0	15·7	Summer
July, 1970	7907	86·7	104·2	17·5	Winter
September, 1970	7806	81·4	100·7	19·3	Spring
April, 1974	8208	79·0	95·0	16·0	Autumn
May, 1975	7806	82·8	98·4	15·6	Autumn
January, 1977	7806	75·8	97·0	21·2	Summer
June, 1978	7806	84·8	102·4	17·6	Winter
December, 1978	7806	93·8	107·1	13·3	Summer

(b)

Date as 1+ Cohort	Fishing Block	Modal Size (mm)		Growth at Mode (mm)	Duration of Growth (months)
		As 1+	As 2+		
February, 1969	7806	85·3	101·3	16·0	18
February, 1973	7907	77·9	100·5	22·6	18
May, 1973	7806	88·0	100·0	12·0	16
January, 1977	7806	75·8	102·4	26·6	17
Mar. 1977	7906	91·4	103·0	11·6	16

age 1+ and 2+. Growth increments were calculated from the difference between modes of a number of pairs of consecutive year classes (Table 2a).

In addition, an attempt was made to compare growth between the 1+ and 2+ modes of several 1+ year classes, followed over a period of approximately 1–2 years (Table 2b). Increments ranged from 11·6 to 26·6 mm added in 1½ years. In the 5 cohorts studied, the period between samples included only 1 season of "fast" growth so that the growth during this period (16 to 18 months) is little different from that during one year. The large variation between growth increments in the above Tables 2a and 2b can be explained by correlation coefficients of –0·75 and –0·908 between the growth of the mode and the 1+ modal size for the Tables 2a and 2b respectively.

5. *Recruitment*

Although mesh selection ogives for the 0+ year class have not been experimentally determined for either type of net in use in Shark Bay, size composition data have indicated that 0+ scallops first become vulnerable

to capture by standard prawn nets in the size range 20 mm + (about July or August) and small quantities of 0+ scallops can be caught even with 102 mm mesh (Robins 1969). The 1+ year class is fully recruited to both types of nets, but the time at which it reaches the minimum processing size ($3\frac{1}{2}$ in. or 89 mm) is highly variable from year to year. It may vary from being of commercial size before or during the "slow" growth season (Figure 7b) to having only half of its members of commercial size by mid year (Figures 7e and 7f) to being poorly recruited as late as September (Figure 7h). Scallops of age 2+ are fully recruited both to prawn and scallop trawl nets and to the fishery because their size range always exceeds both the maximum mesh size used in their capture and the minimum processing size.

TABLE 3—RESULTS OF CORRELATIONS BETWEEN MEAN SHELL HEIGHT AND MEAN SEA DEPTH IN TWO SETS OF SAMPLES OF 1+ SCALLOPS IN SHARK BAY, W.A.

Date	Range of Means		Age	Correlation	Significance	No. of Samples
	Depth (fm)	Shell Ht (mm)				
February, 1973	10·0–24·3	59·8–78·3	1+	—0·80	<·001	18
August, 1974	9·5–13·8	88·9–93·0	1+	—0·25	>·05	12

6. *Effect of depth on mean shell height*

To test if mean shell height for scallops of known age was related to the mean depth from which the sample was trawled, two correlations were undertaken, the results of which are presented in Table 3. Where necessary the 1+ year class, which was dominant and had a prominent mode was separated from the 2+ year class in bimodal samples. In the February 1973 group, mean shell height for 1+ scallops was significantly inversely correlated with depth ($p < \cdot 001$). The correlation from the August group of samples was not significant ($p > \cdot 05$). The main differences between the samples were the range of depths from which they were drawn; the February 1973 samples were drawn from a wider range of depths which were generally deeper than those for the August 1974 samples.

7. *Sex ratios in* Amusium *and the relationship between sex and average shell height*

The sex of saucer scallops cannot be identified from shell shape or other external features, so that sex determination of samples is possible only by inspection of the gonad of mature scallops when in any developing stage. To determine if the sexes were represented in equal numbers, in both 1+ and 2+ scallops, a chi-square test was undertaken in four large bimodal samples. In none of the four samples was the chi-square value significant, indicating that the sex ratio for each age class is 1:1. The same samples were also tested for a significance of difference between the variance in height for males and females of each age class using the variance ratio test, and then the differences in mean shell height between the sexes were tested using Student's *t*-test. In no case was there a significant difference in mean shell height between males and females and in only one sample tested was a significant difference in variance found. A distribution of shell heights, showing males and females separately, is given in Figure 9.

8. *The reproductive cycle and its relationship to growth and age at first sexual maturity*

Table 4 shows the monthly distributions of roe stages from mixed sex samples. The percentage composition by sex in each roe stage was similar and the results for the sexes have been combined. The criteria adopted for classification of roe stages is described fully in Appendix I. The number of roes examined, age composition and height range in each sub-sample is shown. Since 1+ and 2+ scallops are reproductively in phase their results are discussed separately from the results for 0+ scallops which are generally sexually immature (Table 4).

From the 1977 data presented, most 1+ and 2+ scallops were in an early recovery stage (I) in January, but by March had transferred to late recovery (II). From autumn (April) to winter (June to August) most roes examined had progressed from recovery to developing stages (III and IV). By September, 80% of roes were either in late developing (IV) or full stage (V) and 12% were in a ripe pre-spawning condition (VI). The November subsample indicated that most of the scallops were either full (42%, V) or ripe (39%, VI). No sample was available for December 1977.

Data from the reproductive cycle, 1978 (Table 4) showed that three quarters (74%) of scallop roes were ripe in January. In February, most scallops (53%) had returned to early recovery which indicates that spawning had occurred between samples, in late January. In autumn (March and April) most roes were in recovery stages but a small proportion were also either spent (VII) or in early development. A regular transferral through the developing stages was observed in winter sub-samples and by September (early spring) most roes were again in either Stage IV or Stage V. Data for the months of October and November are lacking.

In December, 95% of the roes were in spent (VII) condition and the remainder were in early recovery. Thus spawning in 1978 took place between January 19 and February 8, to complete the 1977 reproductive cycle and before December 22 to complete the 1978 reproductive cycle. Sub-samples examined for roe staging which contained the major proportion in Stage VII have also been encountered in early December 1969 and in mid January 1973. Thus the range of the spawning period from four samples in different years is from early December to late January, i.e. during summer. From this evidence, the average birthdate for all year classes has been arbitrarily chosen as January 1 for the purpose of analyses.

Occasionally small scallops of 0+ age were encountered in sub-samples (August 1977 and December 1978). Roe staging of these showed that in August 1977, 83% were

TABLE 4—THE PERCENTAGE DISTRIBUTION OF ROE DEVELOPMENT STAGES FROM MONTHLY SUB-SAMPLES IN SHARK BAY, W.A. DATA FOR THE 1+ AND 2+ COHORTS ARE SHOWN SEPARATELY FROM THOSE FOR THE 0+ COHORT, WHEN THIS WAS PRESENT IN SAMPLES. THE SUB-SAMPLE SIZE (n) AND SHELL HEIGHT RANGE ARE ALSO SHOWN

(a) 1977

Month	Age	Height Range (mm)	Stages of Roe Development								n
			0 Immature	I Recovery	II Recovery	III Development	IV Development	V Full	VI Ripe	VII Spent	
January	1+, 2+	59–109	2	98	....	....	....	....	....	....	60
March	1+, 2+	86–118	....	25	73	2	....	....	....	....	62
April	1+, 2+	69–115	....	12	38	46	4	....	....	....	50
June	1+, 2+	78–114	....	7	21	49	23	....	....	....	66
July	1+, 2+	63–112	....	....	10	55	35	....	....	....	57
August	0+	31–67	83	....	17	....	....	....	....	....	60
August	1+, 2+	68–116	....	....	2	39	57	2	....	....	70
September	1+, 2+	82–115	....	....	....	8	43	37	12	....	50
November	1+, 2+	75–117	....	....	....	1	18	42	39	....	60

(b) 1978

Month	Age	Height Range (mm)	Stages of Roe Development								n
			0 Immature	I Recovery	II Recovery	III Development	IV Development	V Full	VI Ripe	VII Spent	
January	1+, 2+	79–113	....	....	....	....	20	2	74	4	50
February	1+, 2+	67–113	30	53	5	5	....	....	....	7	60
March	1+, 2+	61–114	1	40	45	9	1	....	1	3	60
April	1+, 2+	57–92	....	36	54	6	....	....	....	4	50
June	1+, 2+	53–117	2	2	6	66	24	....	....	....	50
August	1+, 2+	65–115	....	....	....	42	36	22	....	....	60
September	1+, 2+	87–114	....	....	....	3	40	37	20	....	50
December	0+	43–62	100	....	....	....	....	....	....	....	10
December	1+, 2+	77–114	....	5	....	....	....	....	....	95	40

immature (unsexable) but 17% showed rudimentary sexual development and colouration equivalent to a small Stage II. In December 1978, when 0+ scallops were again encountered in sub-samples, all were immature. Scallops of 0+ age which showed colouration in the August sample were in the size range 55 to 67 mm. A comparison of the largest 0+ scallops which were sexually immature with the smallest 1+ scallops in which it was possible to differentiate the sexes (late Stage II) indicated that *Amusium* roes may begin to develop the colour indicative of sexual maturity in the size range 55–65 mm which is usually between spring in the first year and summer in the second year.

9. *The relationships between total weight, meat yield and shell height*

Relationships between the parameters shell height, whole weight, muscle plus roe weight and muscle weight are presented in Table 5 for (a) a mid-winter sample and (b) a mid-summer sample. These are graphed in Figures 10a and 10b both in roe-on (W_{m+r}) and roe-off (W_m) condition. All pairs of variables tested were strongly correlated ($p < \cdot 001$).

A single scallop which had a severely emaciated adductor muscle which appeared as an outlier in the scattergrams was omitted from the analysis.

TABLE 5—EQUATIONS RELATING SHELL HEIGHT (H), WHOLE WEIGHT (W), ROE-ON MEAT RECOVERY (Wm+r) AND ROE-OFF MEAT RECOVERY (Wm) ARE SHOWN FOR (A) MID-WINTER 1977 AND (B) MID SUMMER 1977 SCALLOPS. THE NUMBERS (N) IN EACH SAMPLE AND CORRELATION COEFFICIENTS (r) ARE ALSO SHOWN. ALL THE EQUATIONS WERE SIGNIFICANT AT THE 0·001 LEVEL

Equations	N	r
(a) Winter 1977:		
$W = 2{\cdot}818\,5 \times 10^{-5} \times H^{3\cdot 1961}$	185	·9968
$W_{m+r} = 1{\cdot}692\,2 \times 10^{-6} \times H^{3\cdot 5186}$	116	·9608
$W_m = 2{\cdot}289\,9 \times 10^{-6} \times H^{3\cdot 4182}$	116	·9603
$W_{m+r} = 0{\cdot}289\,8W - 1{\cdot}560\,6$	116	·9791
$W_m = 0{\cdot}243\,7W - 1{\cdot}095\,9$	116	·9776
$W_m = 0{\cdot}831\,2\,W_{m+r} + 0{\cdot}366\,9$	116	·9870
(b) Summer 1977		
$W = 2{\cdot}737\,0 \times 10^{-6} \times H^{3\cdot 7088}$	60	·9869
$W_{m+r} = 2{\cdot}458\,5 \times 10^{-8} \times H^{4\cdot 4637}$	60	·9836
$W_m = 2{\cdot}266\,0 \times 10^{-8} \times H^{4\cdot 4710}$	60	·9983
$W_{m+r} = 0{\cdot}316\,4W - 1{\cdot}975\,0$	60	·9950
$W_m = 0{\cdot}302\,0W - 1{\cdot}906\,9$	60	·9946
$W_m = 0{\cdot}954\,7W_{m+r} - 0{\cdot}023\,4$	60	·9998

B. Growth data from tagged scallops

Scallops recaptured up to seven days after liberation (all 1971 seasons combined) showed a significant ($p < \cdot 05$) decrease in mean height due undoubtedly to

TABLE 6—MEAN SHELL HEIGHT CHANGES FOR SCALLOPS RECAPTURED AFTER VARIOUS PERIODS OF LIBERTY UP TO 28 DAYS; DATA COMBINED FOR ALL SEASONS IN 1971

Period at Liberty (days)	Height Increment (mm)	Standard Deviation	N
0–7	—0·181 5	0·756 1	92
8–14	0·044 8	1·041 0	67
15–21	0·051 9	1·522 0	27
22–28	0·308 9	1·538 7	45

the effects of shell breakage at release, on recapture and perhaps during both events. Mean shell height did not increase significantly for any period at liberty less than 28 days (Table 6). This may reflect the combined effects of disturbance from handling and tagging and shell breakage in the measured dimension. Thus shell growth rates used in all the analyses may be conservative because of the effect that tagging may have had on shell growth in the scallops.

The released scallops which provided the data were comprised mainly of 1+ scallops with some 2+ scallops (>96 mm) included and only scallops at liberty more than 28 days were used in the following analyses to allow for resumptive growth after tagging.

1. *Seasonal growth*

The linear regression equations of height increase per day at liberty on average height have been plotted in Figure 11 for (a) autumn, (b) winter, (c) spring and (d) summer as defined previously. The combined equation (e) for autumn, winter and spring data is also shown because an analysis of covariance has indicated that no significant difference existed among the slopes and the elevations of regressions for these seasons.

A similar test between the summer regression line and the combined "autumn/winter/spring" line showed a significant difference between their respective slopes and elevations. The growth from tagged scallops at liberty from February to March 1973 and from April to May 1974 more closely resembled the growth shown by the 1971 "autumn/winter/spring" samples than the 1971 "summer" growth. These results lend weight to the concept of a "fast growth" period in the summer and a "slow growth" period in the balance of the year observed in the analysis of height frequency data earlier.

2. *Average growth curve*

An average von Bertalanffy growth curve was obtained from scallops released in 1971 and at liberty approximately one year, using the technique described by Gulland and Holt (1959). This relates some estimate of growth rate to the mid point of the height interval between release and recapture, i.e. $(H_1 + H_2)/2$ where H_1 and H_2 are release and recapture height respectively. Because of the relatively long period at liberty, the iterative technique applying a correction factor to an initial estimate of K was used. Scallops were released in various areas between June and September 1971 and recaptured between May and October 1972 the period at liberty ranging from 315 to 445 days. Five scallops released in 1974 were recaptured 339–436 days later in 1975. These data are quite homogenous because all releases and recaptures were made during the slow growth period, after each scallop had been at liberty for one "full" growth season.

The relationship of growth rate against $(H_1 + H_2)/2$ for the long term data, *ca.* 1 year from both the 1971 and the 1974 releases are shown in Figure 12. The regression line for the 1971 releases which has a correlation of –0·94 is also shown. The growth rate of the 1974 releases, generally larger scallops which have completed most of their growth expectation appears to be similar to that of the 1971 releases. Also shown on Figure 12 are the size differences between the modes for the distribution discussed in Section A4 and Table 2a. These points represent the difference between modes of year classes one year apart expressed as growth rates against the mid point of the two modes, i.e. $(H_1 + H_2)/2$ and are shown to be in close agreement with the growth rate of tagged individuals at liberty for approximately one year. The values for annual K and H_∞ of 1·416 2 and 103·85 mm respectively obtained from the regression of the long term (1972) recaptures were substituted into the von Bertalanffy equations. To complete the equation, an estimate of t_o was made from several height frequency samples of a single year class less than 1 year old. The modal value for H_t from each sample was substituted into the following equations where t is the age of the sample assuming the average spawning time occurs at the beginning of January each year:

$$t_o = \frac{1}{K} \log_e \frac{H_\infty - H_t}{H_\infty}$$

to produce several estimates of t_o (range ·331 to ·399) from which the average estimate of t_o was 0·356.

The fitted equation, which represents average growth for the southern saucer scallop from 1971 (mainly as 1+) to 1972 (mainly as 2+) is as follows:

$$H_t = 103 \cdot 85 \{1 - e^{-1 \cdot 4162 (t - 0 \cdot 356)}\}$$

Because of the difference between the shell growth rates during "summer" and "winter" periods, the growth which occurs during any 12 month period of a saucer scallop's life is a combination of a period of slow growth mainly in the autumn, winter and early spring and fast growth occurring in the "summer" months. Thus the average von Bertalanffy curve can be considered as two different growth curves combined, one which describes "summer" growth and the other "winter" growth. The estimates of the von Bertalanffy parameters for these two distinct periods have been obtained from tagging data within each of the "summer" and "winter" seasons (Figure 11) and their respective durations have been estimated from the times of release and recapture of tags in the two periods as April to September and October to March respectively.

Assuming that at age 1 year, both the average and the seasonal von Bertalanffy growth curves should intersect, then estimates of the height at age 2 can be calculated using either (1) the average growth curve or (2) the seasonal curve (Figure 13).

To estimate the height at age 2 from the height at age 1 the year was divided into three periods, i.e. three months of "summer" growth (January–March), six months of "winter" growth (April to September) followed by three months of "summer" growth (October to December). Starting from a height of 62·1 mm at age 1 the expected average height at age 2 from these two independent methods was 101·4 mm from the annual growth curve and 98·6 mm from the seasonal growth curve (Figure 13).

TABLE 7—A COMPARISON OF THE VALUES OF K AND H_∞ PRODUCED BY (a) THE GULLAND AND HOLT REGRESSION WITH SLOPE CORRECTION B/TANH b AND (b) THE MANZER-TAYLOR REGRESSION, USING THE SAME DATA SET, 1971 RELEASES AT LIBERTY *ca.* 1 YEAR

Method	N	K Annual	H_∞
Gulland & Holt	29	1·416 2	103·85
Manzer-Taylor	29	1·293 6	104·10

3. *Derivation of H_∞ and K by another method*

The same long term data from 1971 releases were used in regressions of H_2 on H_1 (see Manzer and Taylor 1947). The linear regression for the 1971 data using the Manzer-Taylor method was:

$$H_2 = 77{\cdot}237\,6 + 0{\cdot}257\,4H_1$$

Estimates for K and H_∞ derived from this method are in reasonable agreement with estimates from the Gulland and Holt method (Table 7).

4. *Relative growth of individual tagged scallops*

On one occasion it was possible to compare the growth rates of six tagged scallops which were released and recaptured at identical times, in the same area. Figure 14 compares the relative shell growth of scallops, tagged and released as 0+ in spring 1971, block 7706 and recaptured as 1+ in late winter 1972, with their position within the height frequency distributions at release and recapture. All six scallops tended to maintain their relative positions within the height frequency distribution at recapture. Hancock (1967) also found that individual cockles *Cardium edule* maintained their position in relation to others in the distribution over one year's growth.

IV DISCUSSION AND CONCLUSION

External factors such as latitude, temperature, salinity, oxygen and light levels, turbidity, phytoplankton and detritus availability, population density, current speed and water exchange and internal factors such as age, parasitic infection, disease and physiological condition contribute varying degrees of influence to growth and rate of growth in scallops. Many of these are interdependent and thus should not be considered in isolation when determining the importance of each. Seasonal changes in the environment bring about progressive though subtle changes in the levels of these factors, the effects of which are, in turn modified by diurnal rhythms in growth.

It is not within the scope of this study to examine the characteristic pattern of growth shown by *Amusium balloti* in controlled experimental conditions. However, the interpretation of the results from size composition analysis and tagging in terms of the influences of season, age and reproductive cycle does provide a reasonable explanation for the pattern observed.

Seasonal variation in the shell growth rate of other species of scallops in oceanic conditions has also been reported by Golikov and Scarlato (1970) for *Mizuhopecten yessoensis*, Pickett and Franklin (1975), for *Chlamys opercularis* and generally for other temperate water lamellibranchs. Mason (1957) concluded that the growth rate of *Pecten maximus* was influenced by temperature and it is known that the maximum growth rate of the bay scallop, *Aequipecten irradians*, of 6–8 mm per month occurs during the five months of high water temperatures (Sastry 1966; Castagna and Duggan 1971). Hamai (1935a), working with the clam *Meretrix meretrix* found that growth rate was directly correlated with temperature in the species but he also showed that for a fixed temperature, the rate of growth decreases as the season advances. Kirby-Smith and Barber (1974) in experiments undertaken with the bay scallop in which individual scallops were held in a separate compartment in a series of 4 growth chambers at 10°, 16°, 22°, 28°—temperatures within the normal range experienced by this scallop in its natural habitat—clearly demonstrated that growth rate in this scallop was a direct function of temperature in the presence of surplus phytoplankton. Growth rate at 16° was also found to be three times the rate found at 10°.

In the present study, the seasonal nature of growth by 1+ *Amusium* was shown by a period of slow growth from April to August 1970 (Figures 5a–5f), and by a period of fast growth in the balance of the year, shown best by the "summer" regression line of growth rate on mid point of release and recapture height (Figure 11). If one assumes that food supply is not a limiting factor for Shark Bay *Amusium*, then the major component of seasonal effect on shell growth rate in *Amusium* is likely to be the bottom temperature of its habitat.

The Shark Bay saucer scallop population lies in a region seasonally exposed to both oceanic and metahaline waters (Logan and Cebulski 1970). It can be seen from Figure 4 however that the main part of the population, at least that which is usually exploited and has provided all the samples, occurs in the oceanic zone. The seasonal bottom temperature profile from this region is poorly known, but in hydrographic surveys undertaken by Logan and Cebulski, the gross temperature characteristics ranged from a late winter minimum of 19°–20°C (in August) to an autumn maximum of 24°–25°C (in March to May). Figure 5 indicates that significant shell growth resumes just after the annual minimum bottom temperature has occurred in August. However, if there was a direct correlation between water temperature and shell growth in *Amusium* the rate of growth in April and May should have been high because the maximum bottom temperature occurs during this period but this was not the case. The general lack of height frequency data and recaptures from tagging from October to March does not allow any relationship occurring between temperature and shell growth to be readily determined. If shell growth rate lagged behind ambient temperatures (cf. Kirby-Smith and Barber 1974) one would expect the enhanced growth rate from higher temperatures to continue past the period of maximum temperatures for a short time until a "steady state" condition was reached. This was not found in the Shark Bay scallops since growth rate was generally low in the period after the peak temperature in autumn. Further conjecture would be unwarranted without improved bottom temperature data.

Differences have been observed in the spatial pattern and strength of settlement of different year classes of *Amusium* (Figure 6) in concurrence with the findings of Tunbridge (1968) for *Pecten novozealandiae* and with data used by Caddy (1975) to develop a spatial distributional model for the Georges Bank sea scallop fishery. The strength of the emergent 1+ year class in different areas within Shark Bay is likely to be determined completely by the currents and tidal movements

which transport the larvae during their pelagic development. Olsen (1955) used scuba to investigate a population of *Pecten fumata* in D'Entrecasteaux Channel, Tasmania and states: "Water movements, particularly tidal currents, have a marked influence on the distribution of spat. In areas of strong tides, the areas of high concentration run lengthwise to the flow."

Density contours for *Amusium* showed this type of spatial orientation in relation to the pattern of ebb-flood tidal movements in Shark Bay (Penn and Caputi, pers. comm.). It might also follow that larval *Amusium* would be concentrated by eddy systems. The more regular settlement of *Amusium* in the vicinity of block 7806 than elsewhere could reflect the regular development of an eddy system in this area. Differences in the pattern of settlement of successive year classes have an important implication for the Shark Bay fishery. Trawling directed specifically at scallops is first undertaken each year in areas where maximum catch rates (of 2+ scallops) are experienced. Analysis of catch and effort data (Heald, unpublished data) has shown that a considerable reduction in the catch rate of 2+ scallops takes place during each fishing season directly as a result of fishing mortality—this is most evident towards the end of each season. In order to maintain the best catch rates and most economic fishing, exploratory trawling must then be undertaken to locate alternative beds which are sited differently each year. The location of these alternative fishing areas containing a high proportion of still undersized 1+, but with lower than optimum density of 2+ scallops, could be identified by trawlers engaged in prawn fishing as early as February, and used as a guide for scallop fishing later in the season.

A definitive study of the influence of water currents on scallop growth rate was undertaken by Kirby-Smith (1972) using bay scallops which occur predominently in estuarine systems associated with seagrass beds. He postulated that seagrass colonies reduce the effects of tidal currents near the substrate thereby favouring growth. Experiments showed that growth ceased under the most rapid current speed (12 cm/sec) but reached a maximum at the slowest speed of 0·21 cm/sec, due probably to improvements in the efficiency of gill filtration at the slower speeds tested and to silt particle bombardment interfering with filtration at the highest speed. It is reasonable to assume that scallop species occupying different ecological niches, e.g. open sea c.f. estuarine, would each be adapted best for feeding in the range of current speeds encountered in their respective habitats.

Analysis of tagging and size composition data has shown that the southern saucer scallop in Shark Bay has a life expectancy of generally less than 3 years from larval settlement (Figure 8). Both natural and fishing mortality in certain areas combine to reduce the numbers of 2+ scallops in the population. The presence of the 2+ year class as a distinct entity has been seen in samples as late as about 35 months of age but their survival to the following year is extremely rare. In comparison with other species of scallops which have been commercially harvested (Table 8), *Amusium balloti* in Shark Bay can be classified as a short-lived species. From the time scallops reach commercial size (at 1·6 years from the average growth curve), there remains a maximum of 1·4 years during which they can be exploited before a substantial reduction from natural mortality occurs. Thus the continuation of the Shark Bay fishery is annually dependent on the success of recruitment, which can be reliably monitored by trawl nets from 1+ age class. The average growth rate during the lifetime of a saucer scallop declines with age (Table 1). A similarity exists between the average growth rates of 0+ and 1+ scallops, seen both from height frequency data and by steep sloped curve of fitted height at age data in the region of 0+ and 1+ and its slope reduction from 2 years of age onwards (Figure 13). In fact, 87% of the total growth increment between the ages of 0·75 and 1·75 years is made during the six months over the "summer" period of growth. Average linear shell growth in *Amusium* is adequately described by the von Bertalanffy equation, but considerable improvements in the prediction of average size within a year can be obtained if allowance is made for seasonal variation in growth rate.

Scallops aged 0+ have been present on relatively few occasions in the hundreds of height frequency samples obtained between 1968 and 1978, yet the strength of the recruit class (1+ scallops) has only been below a level regarded as an acceptable commercial density in 1966 and 1970 (no production in either 1967 or 1971). Migration of 0+ scallops from a separate habitat to the adult (2+) scallop grounds is unlikely as tagging studies on 1+ and 2+ scallops have shown no evidence of migration (see Appendix II) and 0+ scallops have been always found exclusively with 1+ and 2+ scallops to

TABLE 8—A COMPARISON OF LONGEVITY, MAXIMUM SHELL SIZE AND AGE AT FIRST COMMERCIAL SIZE IN EXPLOITED SPECIES OF SCALLOPS, ARRANGED IN ORDER OF INCREASING LONGEVITY

Common Name	Scientific Name	Longevity (years)	Max. Shell Size (mm)	Age at First Commercial Size
Calico scallop	*Argopecten gibbus*	1½–2	90	" 1 year
Bay scallop	*Argopecten irradians*	1½–2	90	" 1 year
Southern saucer scallop	*Amusium balloti*	" 3	116	1½ years
Queen scallop	*Chlamys opercularis*	" 6	77	2 years
New Zealand scallop	*Pecten novaezelandiae*	> 6	>115	2½ years
Japanese scallop	*Patinopecten yessoensis*	> 8	>150	2 years
South African scallop	*Pecten sulcicostatus*†	> 9	122	not yet exploited
Sea scallop	*Placopecten magellanicus*	>12	"200	" 4 years
Commercial scallop	*Pecten fumata**	>12	"110	" 2½ years
Pacific Sea scallop	*Patinopecten caurinus* ‡	"14	>160	3 years
Scallop	*Pecten maximus*	"22	>130	3 years

*Formerly *Notovola meridionalis*
†de Villiers (1976) ‡Haynes and Hitz (1971)

date. In addition, sampling in areas where 0+ scallops have been first reported has produced inconsistent quantities of them in relation to other ages. The variability of these results is thought to reflect their low vulnerability to capture by standard 44/51 mm prawn nets, especially for those 0+ scallops in the size range 20–40 mm and to a low retention frequency by standard (102 mm) scallop trawl nets through mesh selection. It is postulated that the low vulnerability of 0+ class to capture by prawn nets is largely a function of the shell depth, as 50 juvenile 0+ scallops measured had a mean shell depth at the shell centre of 8·2 mm (the mean height was 42·2 mm) compared with a sample of 50, 1+ and 2+ scallops which had a mean shell depth of 22·2 mm (mean shell height 98·1 mm). Thus even if trawl nets were weighted such that their ground ropes were always very close to the bottom, it would be usual for shells of such low profile to more easily pass under the ground rope and escape as the net passed overhead than 1+ and 2+ scallops with their considerably deeper shells. The use of a tickler chain in advance of the ground rope would disturb 0+ scallops by physical contact or vibration disturbance and may promote their escape by swimming. Escape of 20–40 mm 0+ scallops from inside the 44/51 mm prawn trawl net possibly occurs more easily through the wing meshes (51 mm) than those in the codend (44 mm). The overall retention of 0+ scallops in a prawn trawl net will not only depend on the total amount of catch and other benthos which enters it during a trawl but also to some extent on when these small scallops enter with respect to the start of the trawl. Furthermore, in the codend of a prawn trawl the retention of small 0+ scallops might be expected later in the trawl due to the build-up of trash which would tend to occlude the meshes. The infrequent catches of small 0+ scallops in standard (102 mm) scallop nets is probably also due to the progressive filling of the net and mesh occlusion.

The variability of results obtained from the attempted correlations of mean shell height with depth, suggests the need for experimentation with caged scallops held at distinct depths to investigate the relationship. Duggan (1973) suspended trays of the bay scallop at different depths in the water column in an estuarine environment but could find no differences in the growth rates of the experimental groups. Gutsell (1930) also concluded that depth was not an important factor in the growth of this species. Mason (1957) however found that rate of growth in *Pecten maximus* was inversely correlated with increasing depth of water, which he attributed to colder temperatures in deeper water, and the Japanese suspend caged scallops high in the water column where it is implied that superior growth rates are obtained (Taguchi and Walford 1976).

Reproduction and spawning have been examined by macroscopic techniques in *Amusium balloti* (see also Appendix I). *Amusium*, like *Placopecten* (Naidu 1970) has separate sexes. Unlike *Placopecten*, however, individual *Amusium* have never been found in the hermaphroditic state or as accidental functional ambisexuals (Coe 1942). Colouration in male or female scallop roes, indicating the initiation of gametogenesis can start late in the first winter in some larger individuals of 0+ age (shell height 30–35) but the maturation of roes in most scallops usually occurs from the following autumn as 1+ year class. Conversely, the largest 1+ scallop with an immature roe was 62 mm in shell height. The single annual spawning first occurs in the summer when the cohort is approximately two years old. Spawning in most saucer scallops is completed between the start of December and the end of January—there has never been any evidence of partial spawning or regression to pre-spawning developmental stages. The onset of spawning varies each year though it is generally completed within a month during rising benthic sea temperatures.

In contrast to *Placopecten*, the distribution of macroscopic roe stages shows no evidence of protandry.

The relationship between the reproductive cycle and the process of shell growth is interesting in Shark Bay *Amusium*. Unlike shell growth, which is at a maximum over the summer, roe development is active in autumn when there is a significant transition of roes from resting and recovering stages to developmental stages in this period, during which bottom temperatures are highest. In the period May-August when the roes are filling, very little shell growth takes place. In *Amusium* therefore, the lack of shell growth in 1+ and 2+ scallops in the autumn when bottom temperatures are highest, might be explained by the diversion of somatic growth into reproductive effort.

Fitted equations based on the data from a summer sample (January 1977) and two winter samples (July and August 1977) for the inter-relationships of shell height (H), whole weight (W) and meat yield with roe (W_{m+r}) and without roe (W_m) (Tables 5, Figures 10a and 10b) allow predictions such as average meat yield or whole weight from a known height and of slight seasonal differences in recovery over the weight range examined. Because of its rapid growth rate and high meat recovery (*ca.* 20% roe-off and 25% roe on) *Amusium balloti* may be a useful species for mariculture either in an open circuit aquarium or in a closed system, using glasshouse culture techniques to provide phytoplankton of the correct size and nutritional value for larvae and spat.

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APPENDIX I

CRITERIA FOR CLASSIFICATION OF ROE STAGE

Macroscopic classification of *Amusium balloti* roes was adapted from a key produced for *Pecten meridionalis* (= *Pecten fumata*) by A. J. Harrison in Tasmania (Harrison 1961). *Amusium balloti* in Shark Bay is sufficiently unlike *Pecten fumata* in its rate of growth and gonochoristic sexuality that it was thought useful to describe the differences between the stages.

Stage 0 (Immature). Gonads minute, a very thin strip of translucent white tissue. Impossible to distinguish the sexes.

Stage I (Recovering). Gonad very small, i.e. thin narrow and strap-like. Both sexes indistinguishable in colour or shape; gonads are a pale translucent brown. Alimentary tract in gonad completely visible.

Stage II (Recovering). Gonads still straplike but slightly broader, and thicker. Possible to distinguish males which are translucent to opaque cream in colour from females which are translucent brown to pale pinkish brown. Alimentary tract is slightly occluded at proximal end by tissue growth.

Stage III (Developing). Gonads less straplike, thickened in depth towards centre and reasonably broad. Males opaque cream and females pale candy pink. Approximately 60% of alimentary canal obscured—though still visible at distal 1/3 of gonad in either sex.

Stage IV (Developing). Gonads broad and encircling 1/3 of adductor muscle (maximum length attained). Gonads in both sexes acutely shaped at margin. Males cream to fawn in colour and females dark candy pink. About 1/4 to 1/5 of total alimentary canal remains visible at distal end.

Stage V (Full). Gonads fat, i.e. broad and deep. Males are dark cream to beige, females dark candy to crimson red in colour. About 1/8 of alimentary canal visible at distal end of gonad, which is sub-acute to acutely rounded in shape.

Stage VI (Ripe). Gonads very swollen, oval shaped in section. Less than 1/8 of length of alimentary tract exposed at distal tip of gonad, which is rounded. Males dark cream to fawn, females dark candy pink to crimson red. A vein like pattern of ducts visible at 5x magnification on surface of gonads, clearer in females because of contrasting background colour. Surface appearance of gonad granular. Small patches of clear tissue may be irregularly scattered over surface of gonad.

Stage VII (Spent). Gonads large in surface area but much flattened and watery within. Impossible to distinguish male from female gonads. Colour pale transparent brown in all gonads. Alimentary canal entirely visible.

APPENDIX II

MIGRATORY MOVEMENT IN SAUCER SCALLOPS

INTRODUCTION AND METHOD

The study to investigate whether *Amusium* move in a migratory sense was undertaken as part of a broader tagging programme to monitor their growth between 1970 and 1974. Recapture data fell into two categories of precision with respect to release and recapture location. Accurate location may have been determined by radar on both occasions resulting in an error of about ¼ mile radius around each position. The majority of the data however are from less accurately determined release and/or recapture locations and therefore the maximum location accuracy would be at the level of fishing blocks only (see Figure 15) when either the release or recapture vessel did not have radar.

RESULTS AND DISCUSSION

Between 1970 and 1974, a total of 17 734 tagged scallops were liberated within Shark Bay. These provided 1 729 recaptures in total, an overall recovery rate of 9·7%. Of those returned, 1 279 (74%) had suitable location data with them. This figure can be divided into 59 returns (8%) fully located by radar and 1 220 with less precise block data. Although Table 9 included a large number of short term recoveries, recaptured about one month after release, it also included a significant proportion (32%) of medium to long term recoveries in the range 40–204 days. Table 9 is based on 341 recaptures from autumn/winter/spring releases in 1971, 390 recaptures from autumn/summer releases in 1973 and 548 recaptures from autumn releases in 1974.

The data in Table 9 have been placed on a comparative basis by treating recoveries made in the release block as home block, with each adjacent block then assuming one of the eight compass points. The table of this less accurate data suggests that the majority of returns were reported from their home block with some recaptures being reported in blocks immediately adjacent. An error of about three miles radius should be allowed around each of these reported locations—from possibly inaccurate navigation and the distance covered by the trawl. An error of this magnitude, when applied from near the edge of a block could transfer the reported location to within the adjacent block. One scallop (released on block 8007, 1974, recaptured in block 7807, 17 days later) out of 1 279 returns appeared to move significantly. When substantial numbers of scallops were "displaced" to adjacent blocks, e.g. in 1974 23% to the north of 8007; in 1973 32% to the south of block 7607; and in 1971 40% to the north of block 7806; either the release occurred close to the common border between home and adjacent blocks as with the last example or difficulties in position finding were usually experienced from lack of visible light houses and the absence of radar or the fishing effort was unequally distributed around the release site. In Shark Bay, the pattern of trawling is usually N–S but when the fleet is less closely grouped, trawling E–W (e.g. along the prawn nursery line) or along intermediate compass axes may occur and this could provide an explanation for the displacements observed. Another way by which tagged scallops could be transferred to adjacent blocks is by repeated displacement in one direction after being overlooked in the trash. On several occasions, one of the authors witnessed the careless screening of trash for tagged scallops. These scallops would otherwise have been returned to the sea 2–3 miles from their release position.

The 59 returns shown in Figure 15 are from the radar determined release and recapture sites. These centre-of-trawl locations were back-calculated by skippers up to one hour after the scallops capture and therefore need a 2–3 nautical mile radius of error drawn around each point. When this is done, all plotted returns in Figure 15 overlap their release position.

CONCLUSIONS

Evidence on *Amusium* movements presented here suggests that there was a lack of definitive migration occurring in the scallop population in the size range tagged, over periods of up to 1½ years. Position fixing was insufficiently accurate to determine if localised movements occur due to escape from predators or from the influence of tides. Certainly *Amusium* has a well developed swimming ability (pers. comm. B. Wilson, K. Back) and the genus is attributed with special evolutionary adaptations (e.g. light shell, internal ribs) to aid swimming (Waller 1972). The lack of migratory movement found in *Amusium balloti* is in general accord with studies on other species of scallops.

TABLE 9—THE RECAPTURE DISTRIBUTION OF SAUCER SCALLOPS RELEASED IN DIFFERENT BLOCKS, RELATIVE TO THE RELEASE (HOME) BLOCK

Release Details	% Recaptured in home and adjacent blocks									No. of Recaptures
Aut./Wint./Spring 1971	Home	North	N.E.	East	S.E.	South	S.W.	West	N.W.	
Block—										
7607	25	....	....	....	....	....	75	....	....	3
7707	73	....	....	....	....	19	....	8	....	26
7706	85	3	....	6	2	4	....	....	....	150
7806	45	40	....	10	....	....	....	....	5	76
7807	80	2	....	....	....	12	....	2	4	84
7907	50	50	....	....	....	....	....	....	....	2
Total recaptures	....	....	....	....	....	....	....	....	....	341

Release Details	% Recaptured in home and adjacent blocks									No. of Recaptures
Sum./ Aut. 1973	Home	North	N.E.	East	S.E.	South	S.W.	West	N.W.	
Block—										
7607	48	....	....	....	....	32	15	5	....	117
7707	95	1	....	....	....	....	....	4	....	75
7706	59	1	....	30	2	....	....	....	8	94
7806	62	25	....	....	....	1	....	8	4	78
7807	50	50	....	....	....	....	....	....	....	2
7907	92	2	....	....	2	4	....	....	....	24
Total recaptures	....	....	....	....	....	....	....	....	....	390

Release Details	% Recaptured in home and adjacent blocks									No. of Recaptures
Autumn 1974	Home	North	N.E.	East	S.E.	South	S.W.	West	N.W.	
Block—										
7606	50	....	....	....	....	50	....	....	....	2
7706	40	....	....	60	....	....	....	....	....	5
7807	96	....	....	....	....	4	....	....	....	48
7907	98	....	....	....	2	....	....	....	....	53
8007	53	23*	2	20	1	....	....	....	....	94
8008	87	3	....	....	5	....	....	2	3	205
8108	90	....	....	10	....	....	....	....	....	137
8109	75	....	....	....	....	....	....	25	....	4
Total recaptures	....	....	....	....	....	....	....	....	....	548

* One scallop reported to be recaptured ten miles north of release.

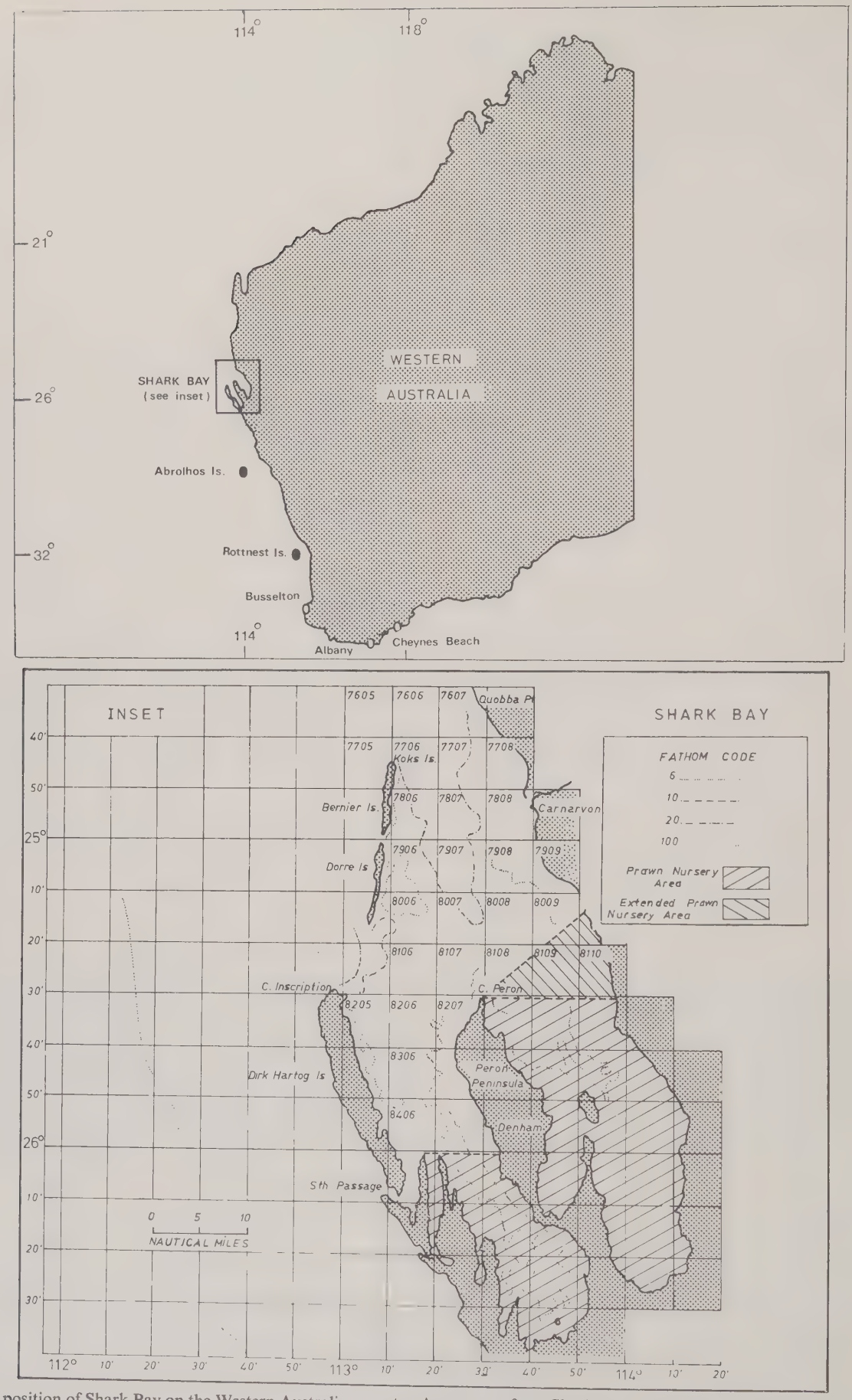

Fig. 1—The position of Shark Bay on the Western Australian coast. Areas apart from Shark Bay from which commercial landings of saucer scallops have been taken (solid dots) and areas from which the presence of saucer scallops has been confirmed by live specimens (open circles) are also shown. The insert of Shark Bay shows its division into 10 mile by 10 mile fishing blocks, the nursery area for prawns permanently closed to all trawling and depth contours in the bay.

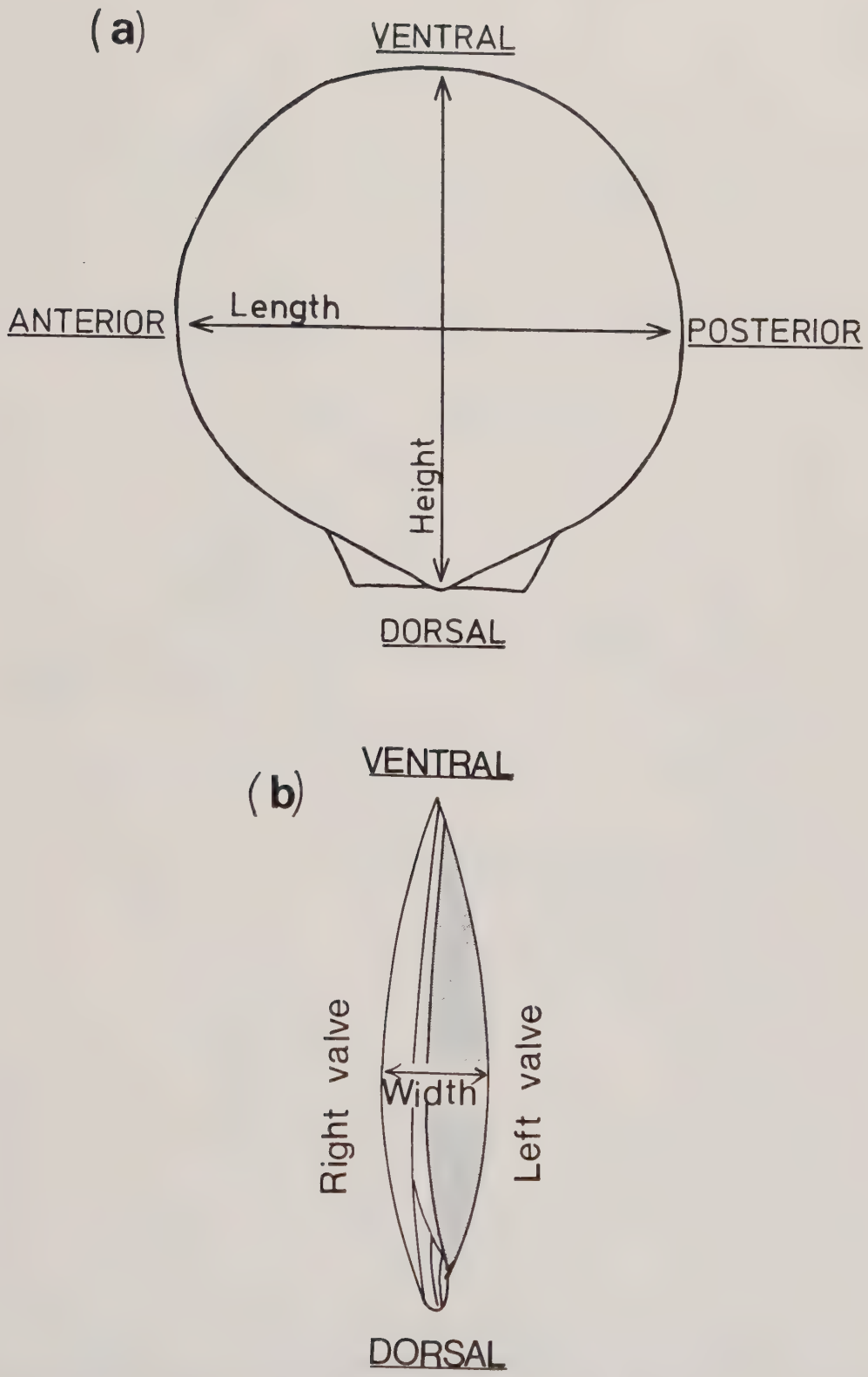

Fig. 2—Shell dimensions of the southern saucer scallop, *Amusium balloti*, showing (a) view of upper valve from above and (b) view of valve pair from the edge.

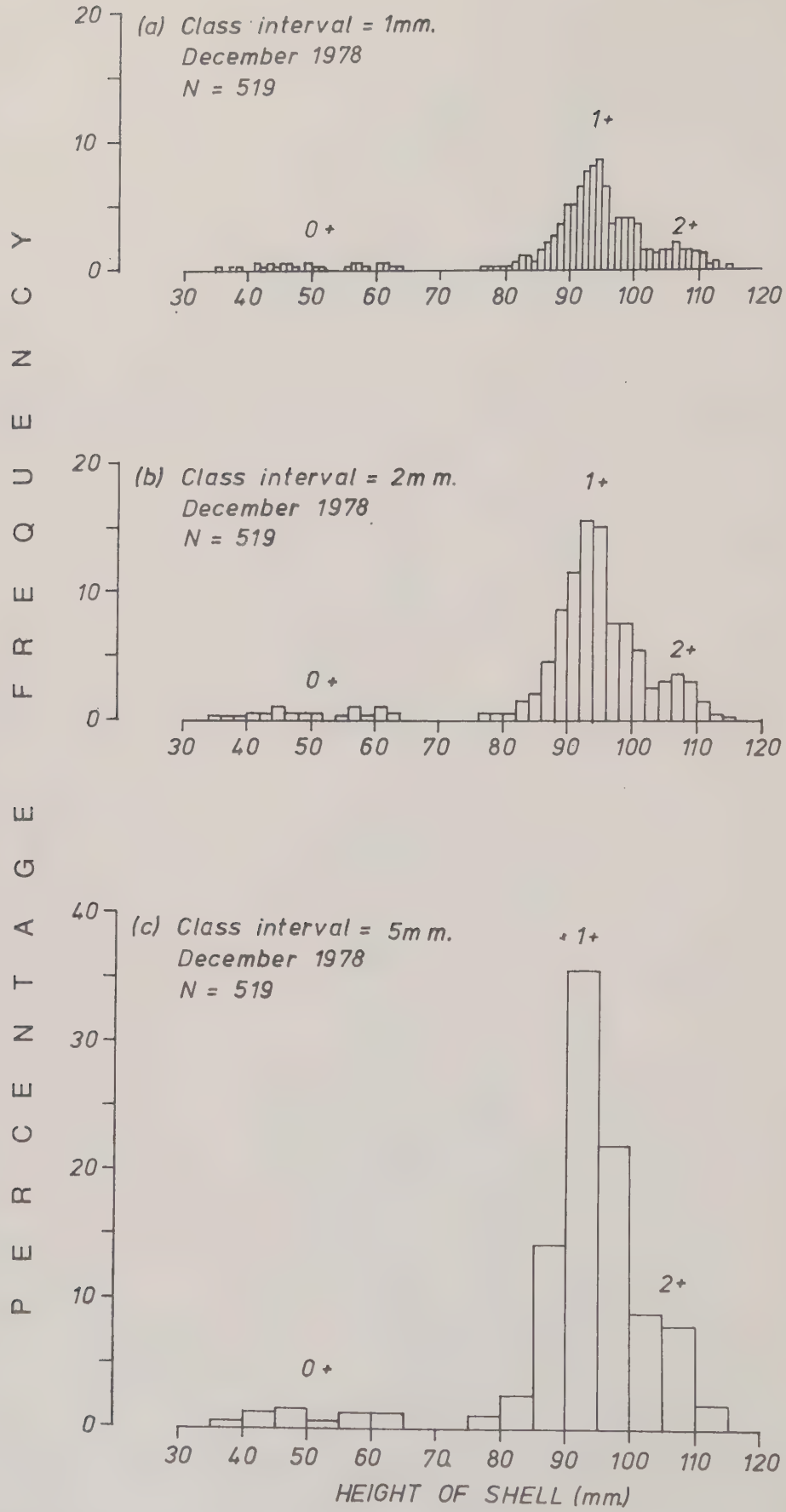

Fig. 3—Comparison of different choices of class interval width in their ability to distinguish year classes in a single polymodal height frequency of scallops, originally measured in whole millimetres.

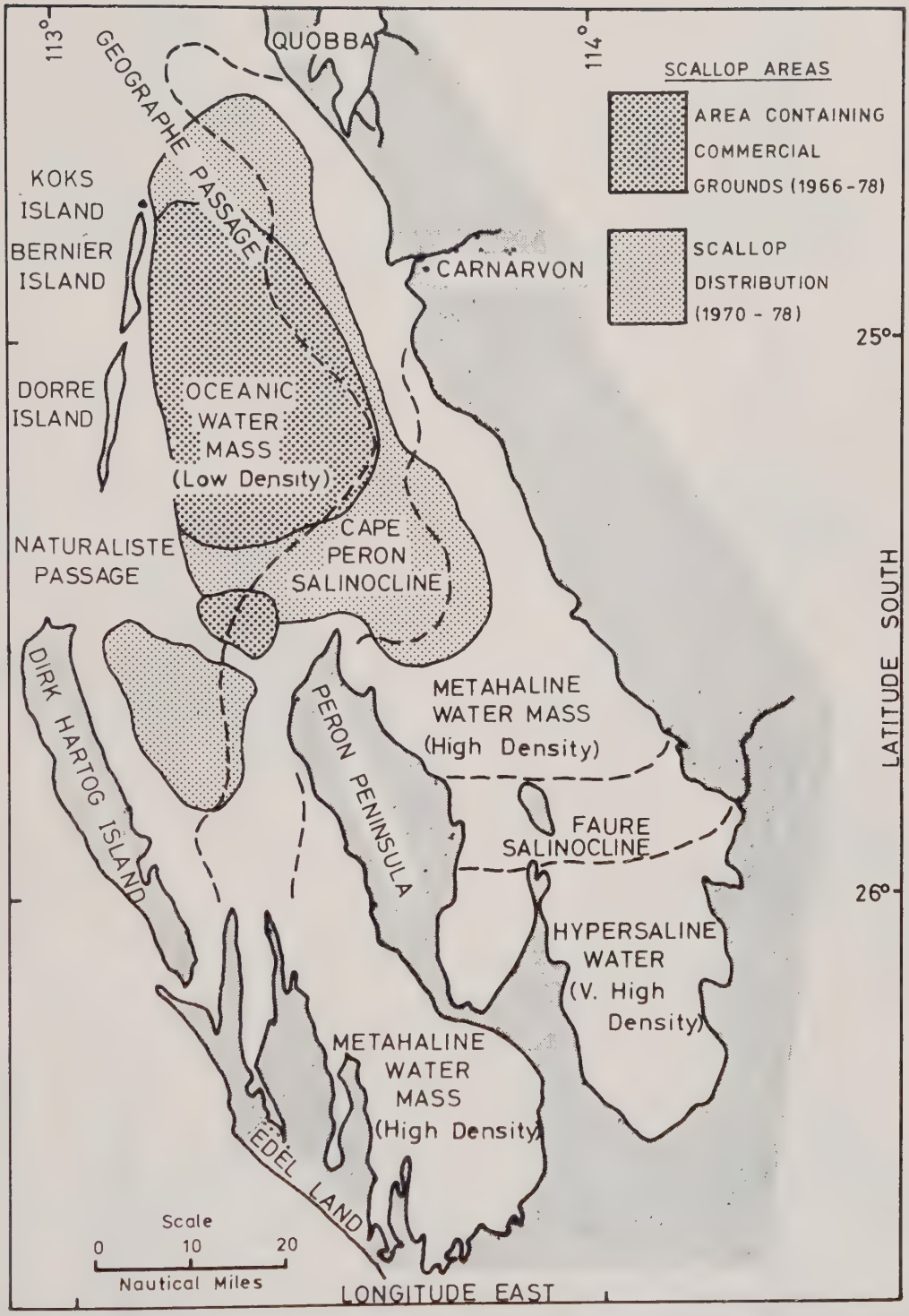

Fig. 4—The distribution in Shark Bay of the southern saucer scallop population as revealed by sampling and research logbook records from 1970 to 1978 is shown together with areas containing grounds of commercial abundance from 1966 to 1978, superimposed on regions of differing water density, separated by dotted lines (modified from Logan and Cebulski 1970, Figure 8).

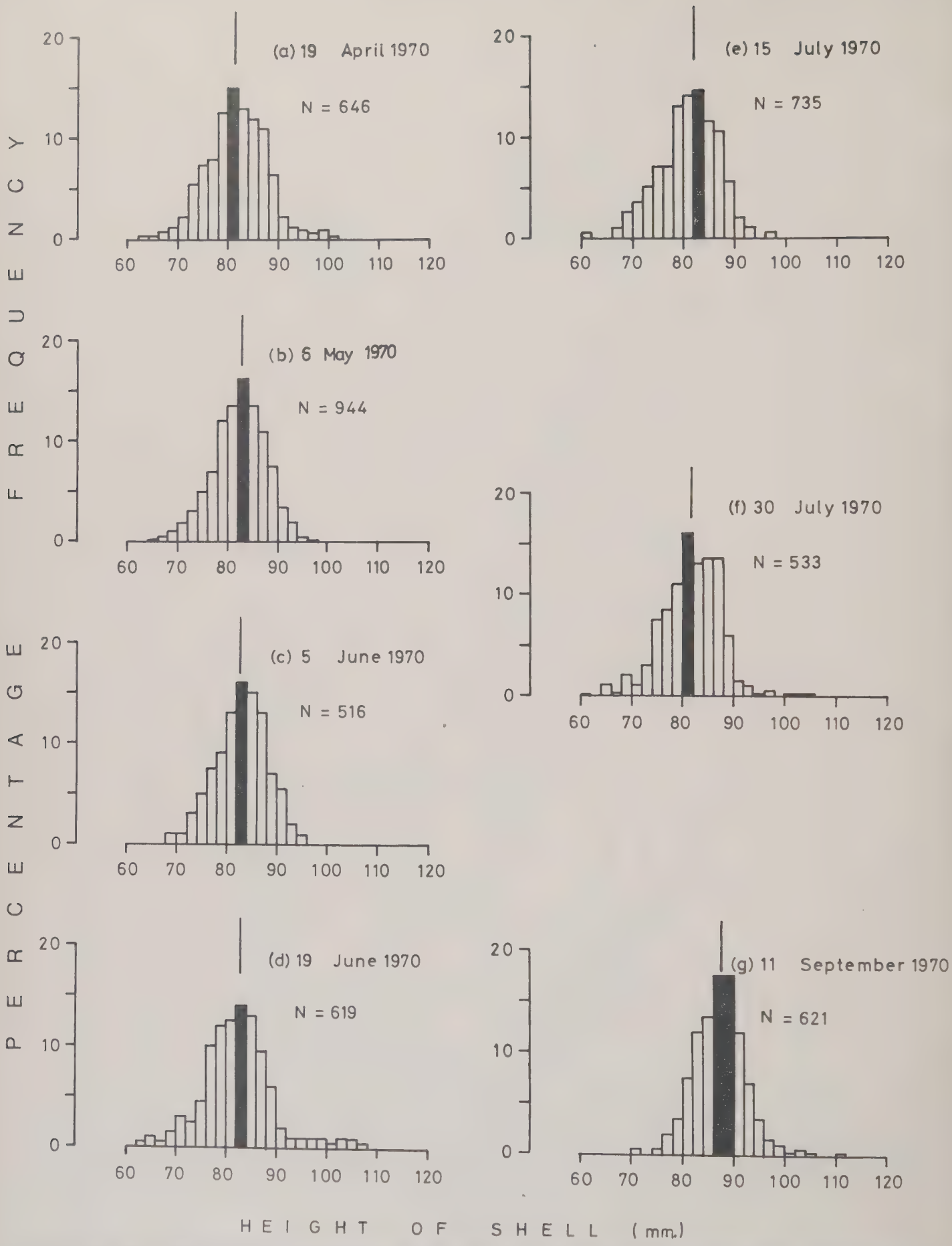

Fig. 5—The positions of the mode (shaded column) and mean shell height (vertical line) are compared in height frequency histograms of 1+ scallops between April and September, 1970 (August excluded) from fishing block 7807 in Shark Bay. All samples were provided by prawn trawlers using 44mm/51mm mesh and none were culled by hand.

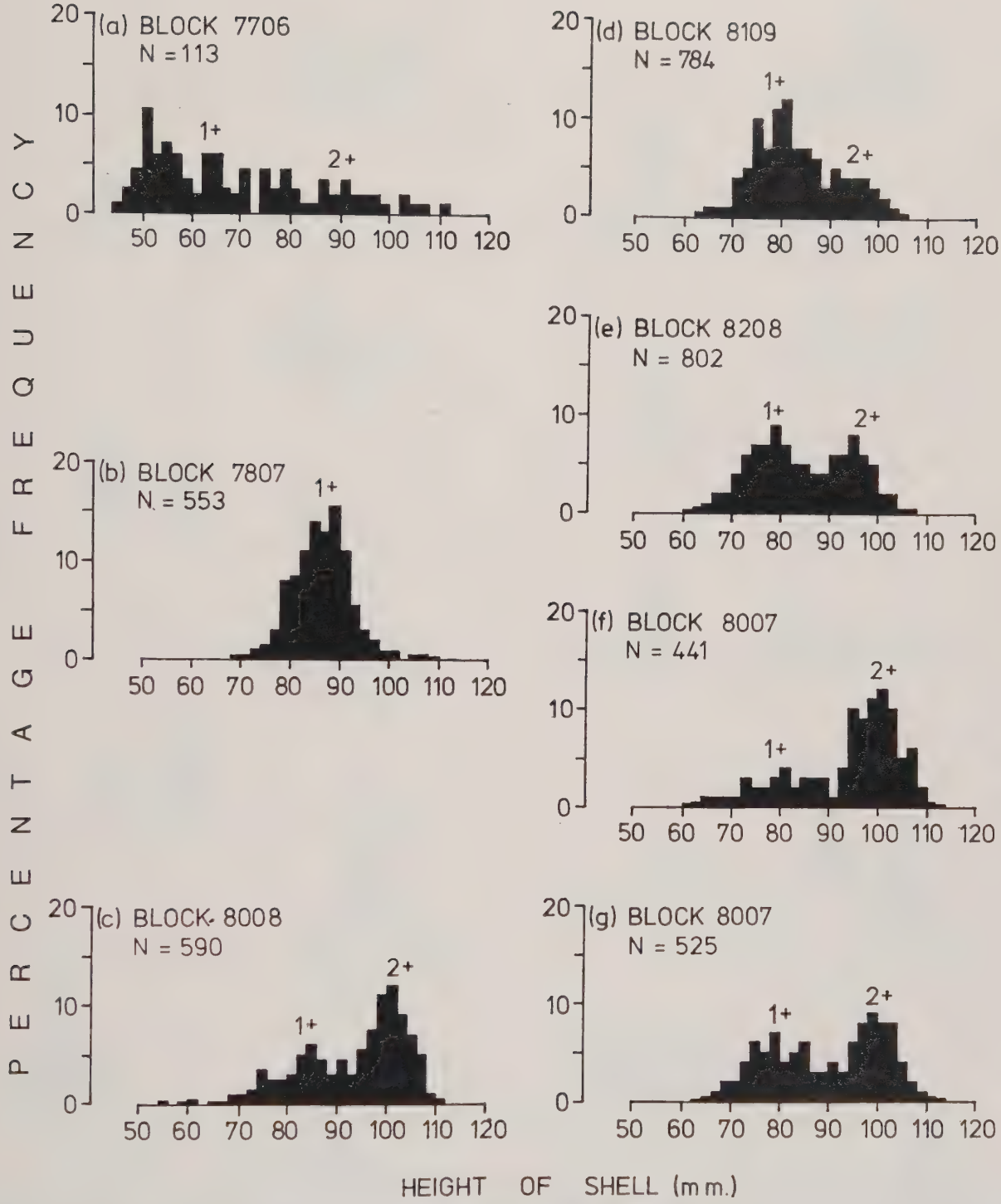

Fig. 6—The relative abundance and size of the 1+ and 2+ year classes in Shark Bay in April, 1974 from various fishing blocks. The 2+ year class had not been fished the year before in any of the areas sampled. Samples were obtained, tagged, measured and released from the same trawler using standard prawn trawl nets of 44mm/51mm mesh. Position within the fishing blocks was fixed by radar.

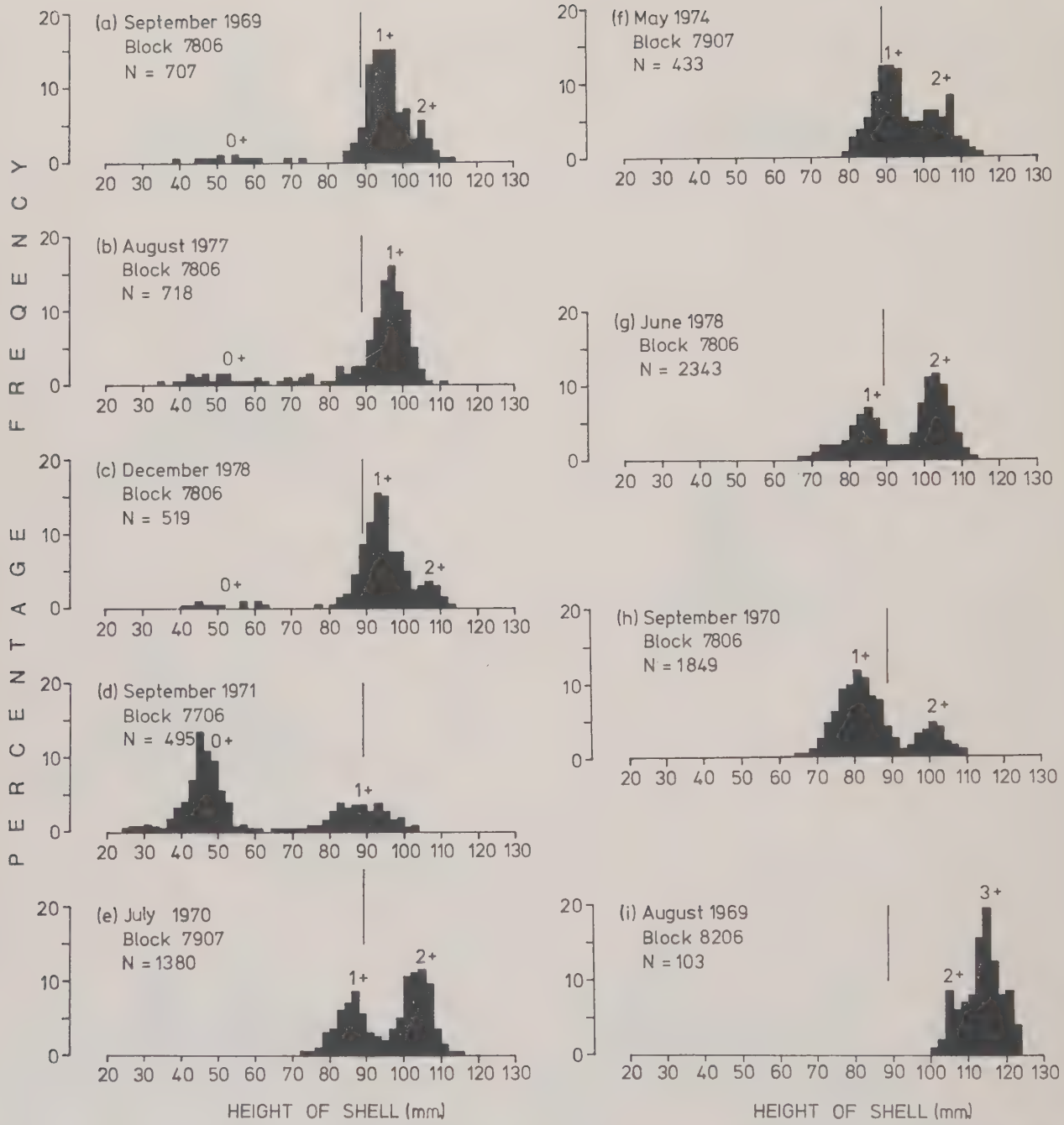

Fig. 7—Combinations of year classes in polymodal height frequency distributions from different fishing blocks in various years in Shark Bay. The minimum size accepted for processing is shown by a vertical line above each histogram. All samples were taken by 44mm/51mm mesh trawl nets and none were culled by hand.

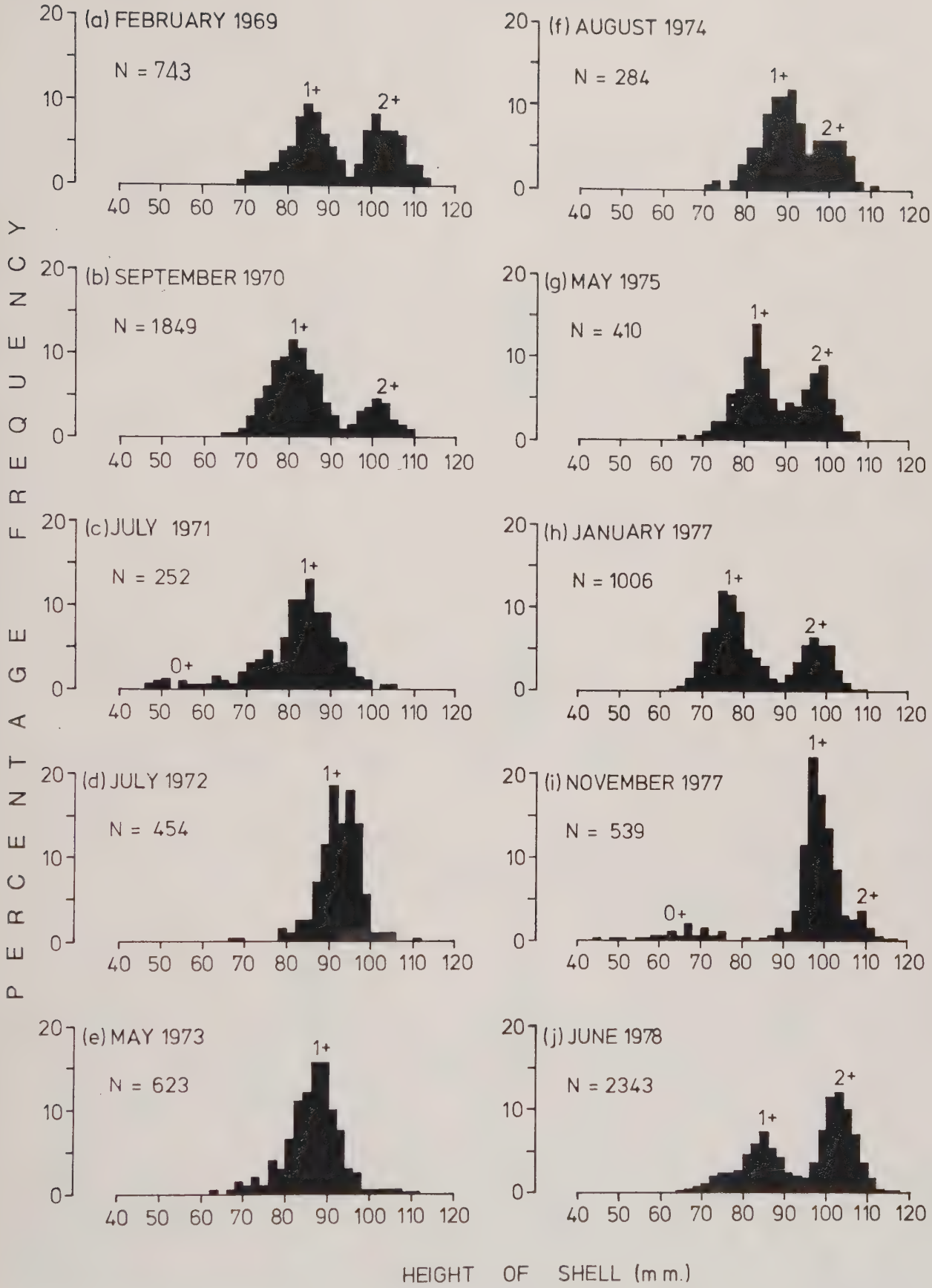

Fig. 8—Changes with time in the height frequency distributions of polymodal samples of southern saucer scallops in fishing block 7806, between 1969 and 1978.

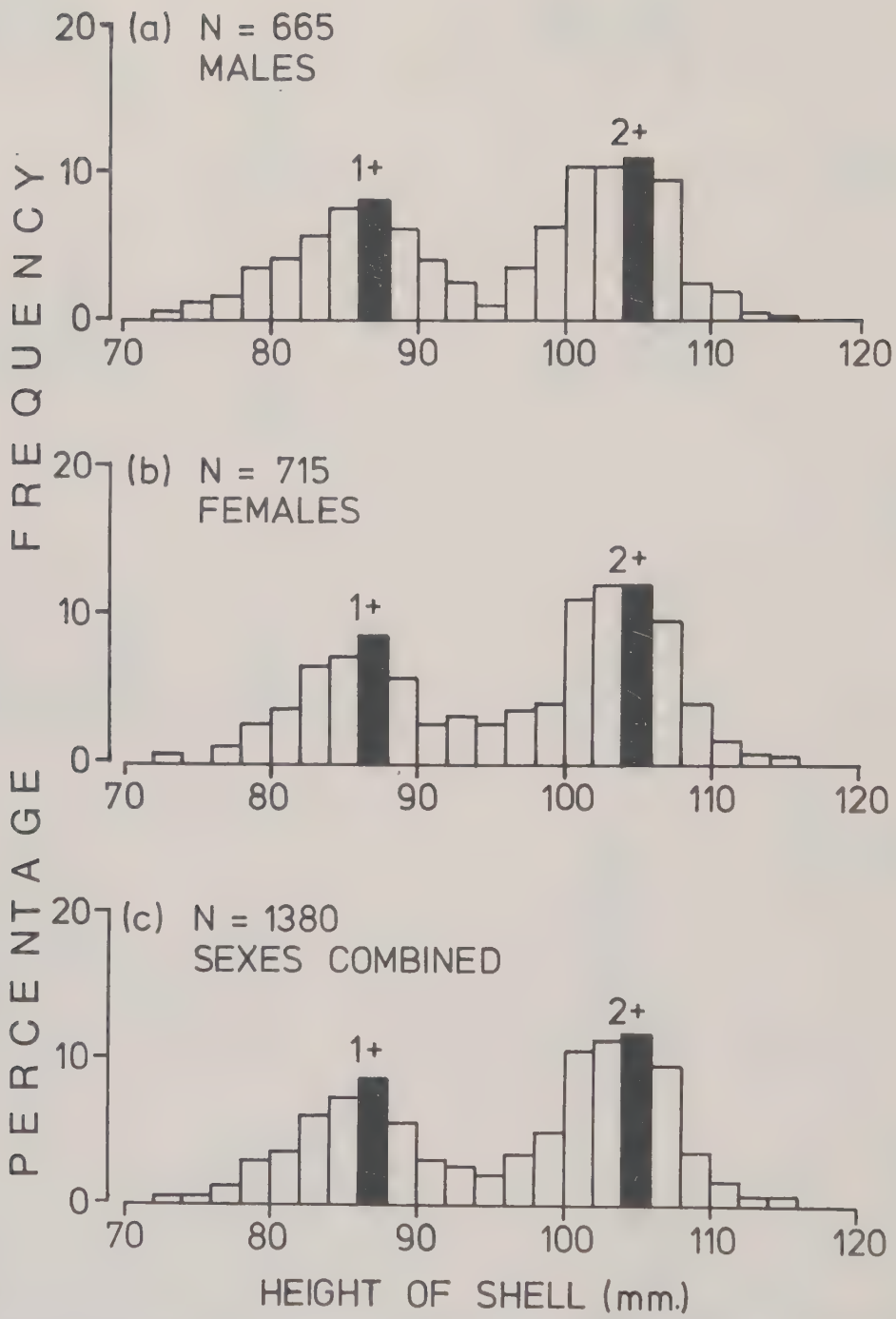

Fig. 9—Height frequency distributions for one typical sample of scallops in which the sexes have been measured separately; showing (a) males, (b) females, (c) sexes combined. The modal classes for the 1+ cohort and 2+ cohort are shown by solid shading.

Fig. 10a—Fitted curves of the relationships among shell height H(mm), whole weight W (gm), muscle and roe weight W_{m+r}(gm) and muscle weight W_m(gm) are shown separately for summer data (broken line) and winter data (solid line). These correspond with equations shown in Table 5.

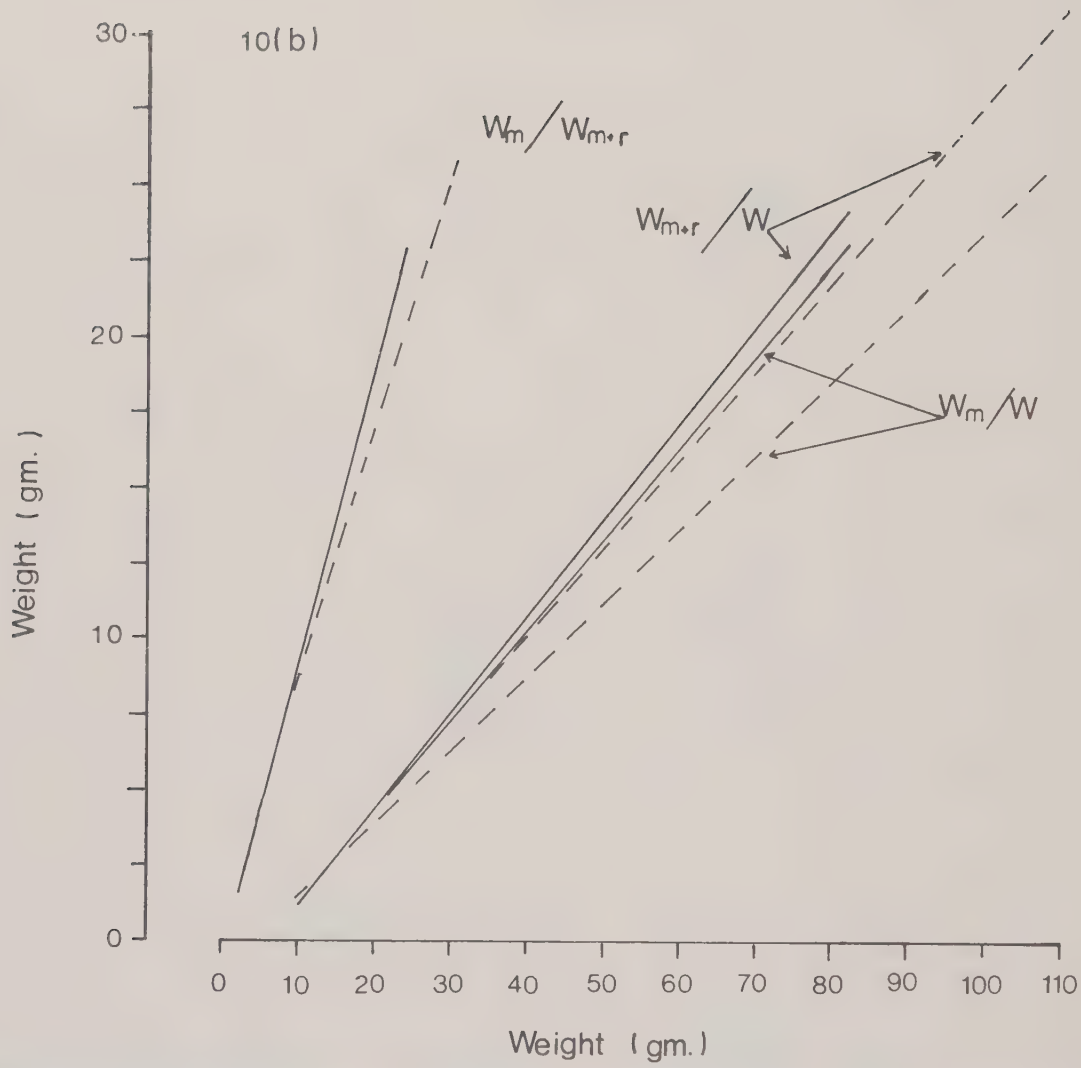

Fig. 10b—Fitted curves of the relationships among whole weight W(gm), muscle and roe weight W_{m+r}(gm) and muscle weight W_m(gm) are shown separately for summer data (broken line) and winter data (solid line). These correspond with equations shown in Table 5.

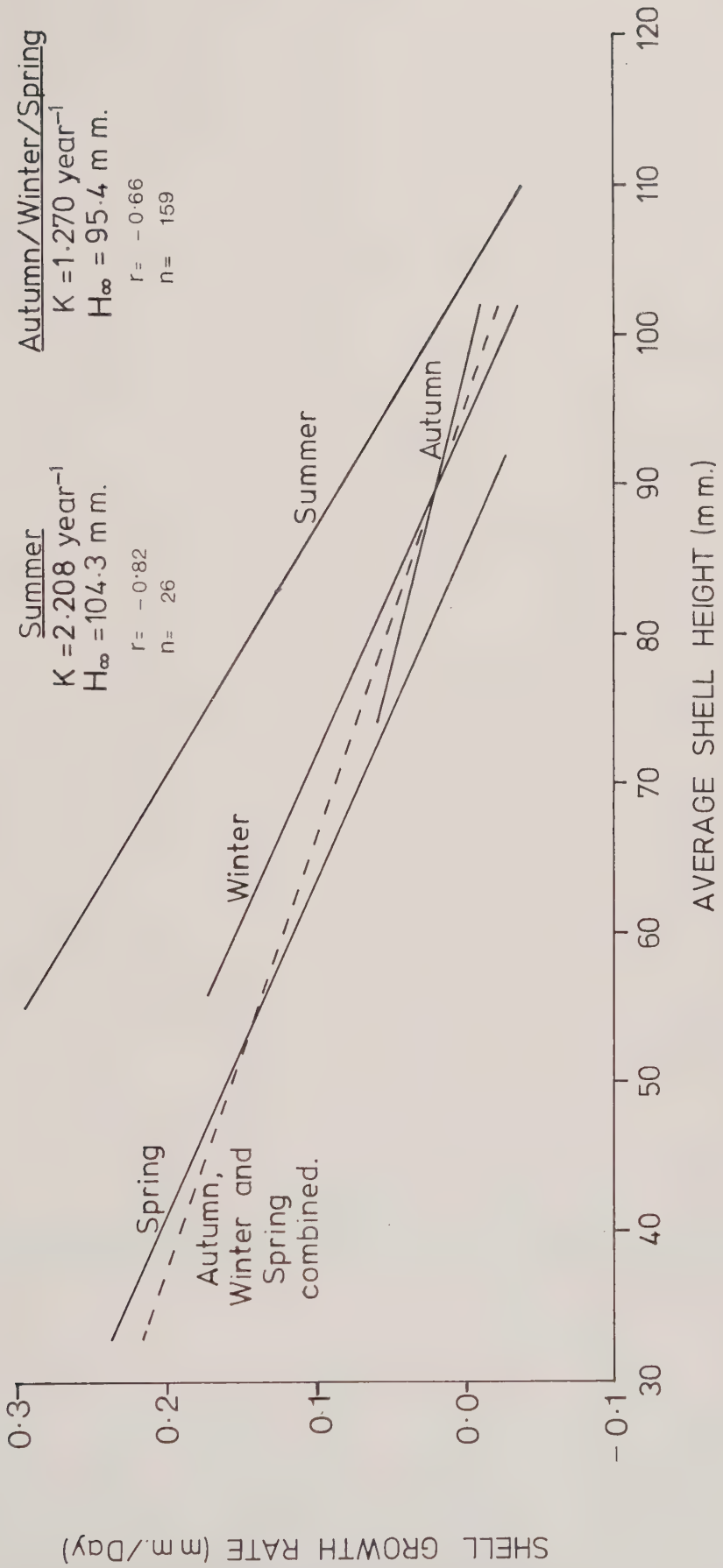

Fig. 11—Regressions of growth rate (mm/day) on average height at liberty (mm), from recapture data. The data have been grouped into seasons according to when the major period at liberty occurred. The combined autumn/winter/spring regression is shown by a broken line. All data were from returns for which the period at liberty exceeded 28 days. von Bertalanffy parameters K and H_∞ are shown as well as the correlation coefficient (r) and sample size (n) for the summer and autumn/winter/spring lines.

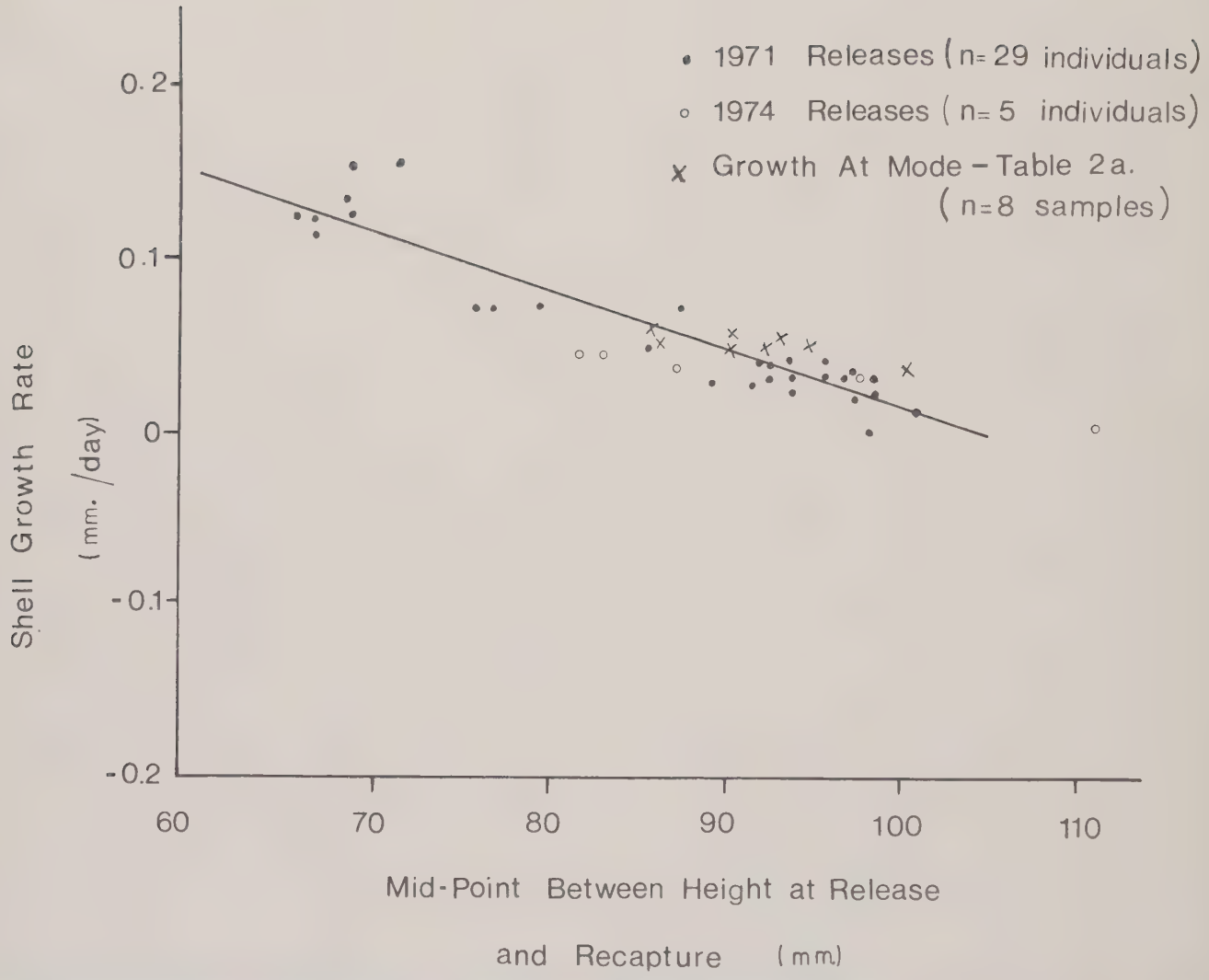

Fig. 12—Relationship between growth rate (mm/day) and mid-point of height interval between release and recapture i.e. $(H_1 + H_2)/2$ for recaptures at liberty *ca.* 1 year based on the 1971 and 1974 releases. The regression line for the 1971 releases is shown. Differences between modes of 1+ and 2+ year classes (see Table 2a) expressed in terms of growth rate against the mid-point of the two modes are also shown.

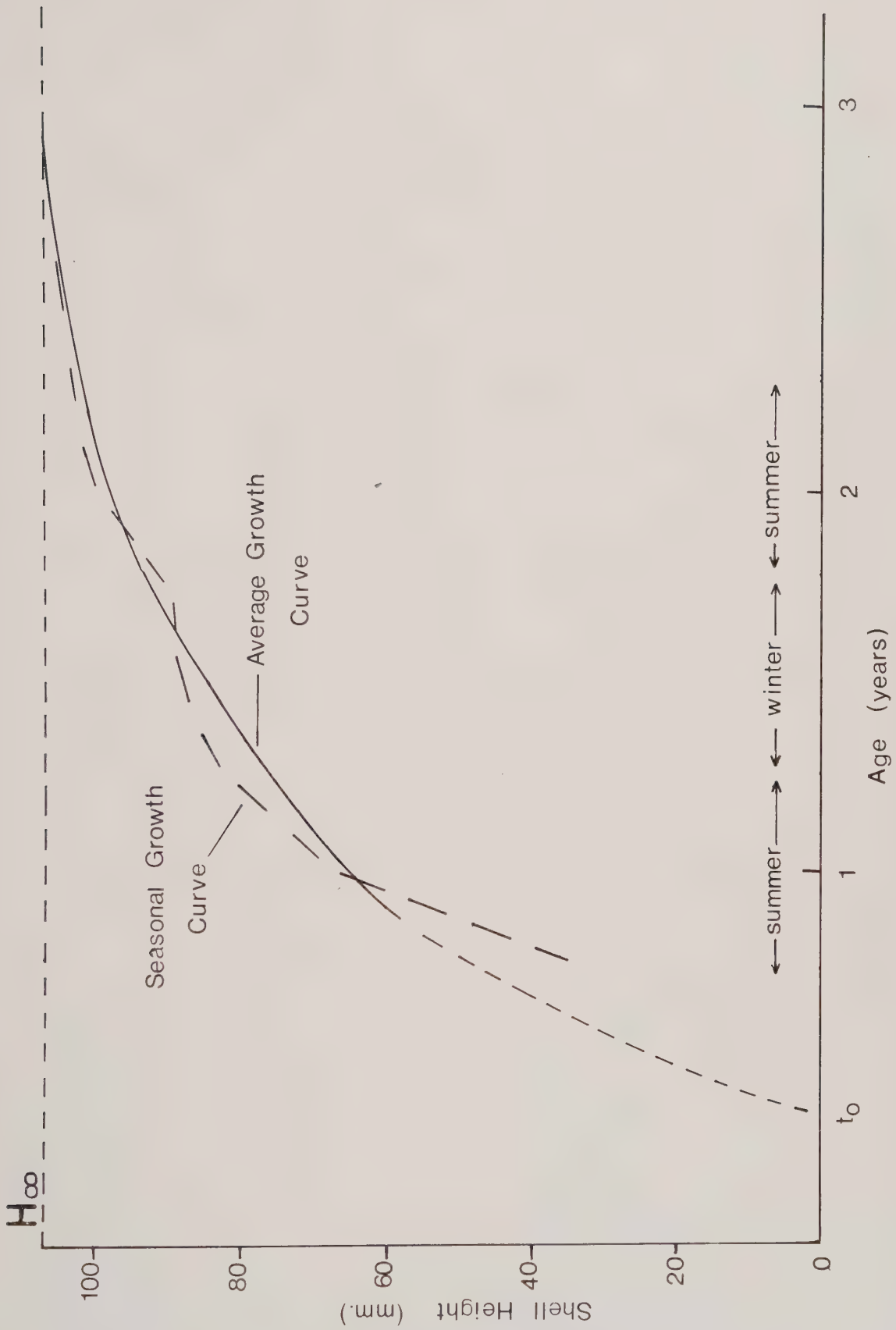

Fig. 13—The average von Bertalanffy growth curve for *Amusium balloti* based on recaptures at liberty approximately 1 year (solid line) and the curve based on seasonal recaptures (broken line).

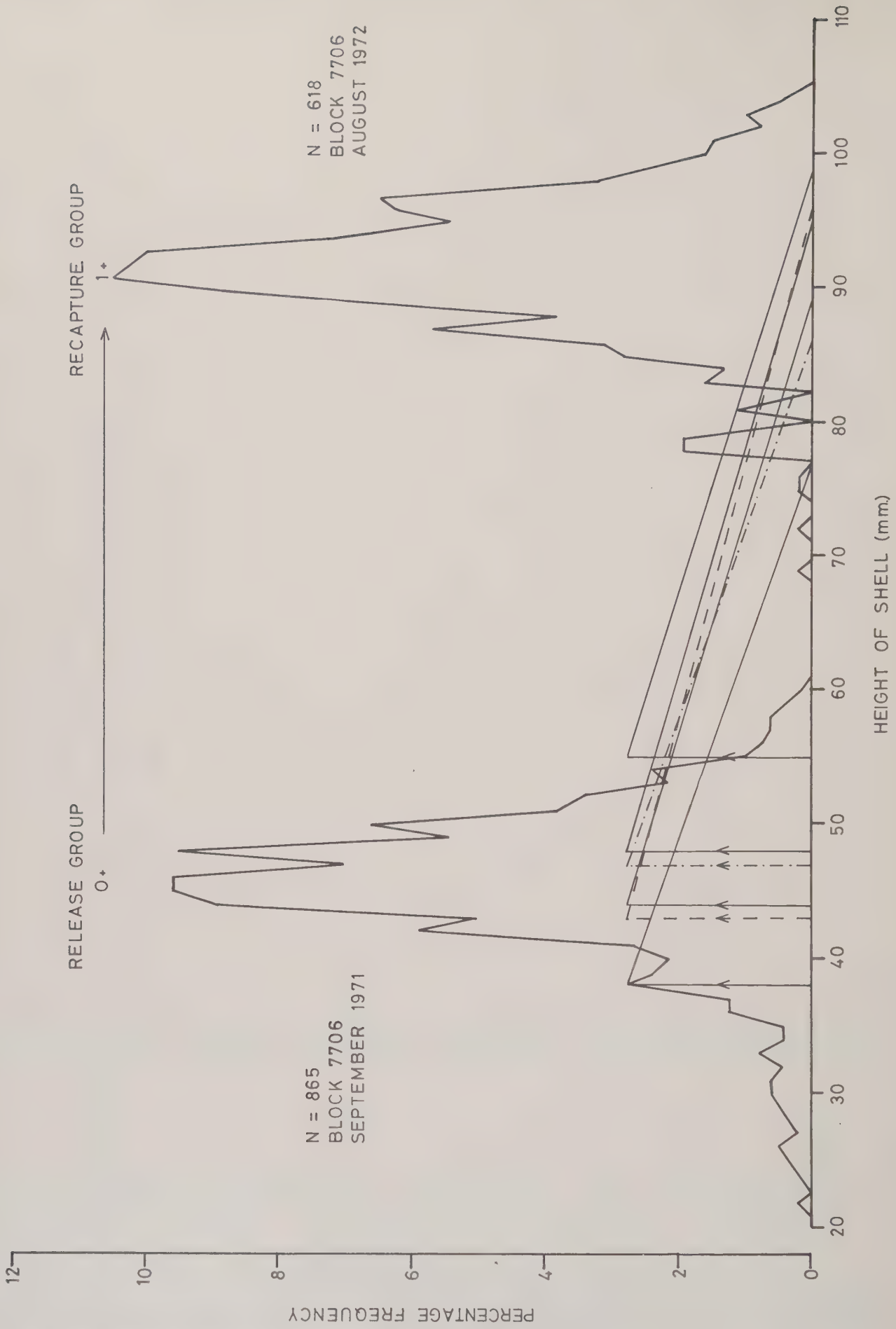

Fig. 14—The shell heights of 6 tagged scallops are compared with the height frequency distribution of the total sample at release as 0+ in September 1971 and at recapture as 1+ in August 1972.

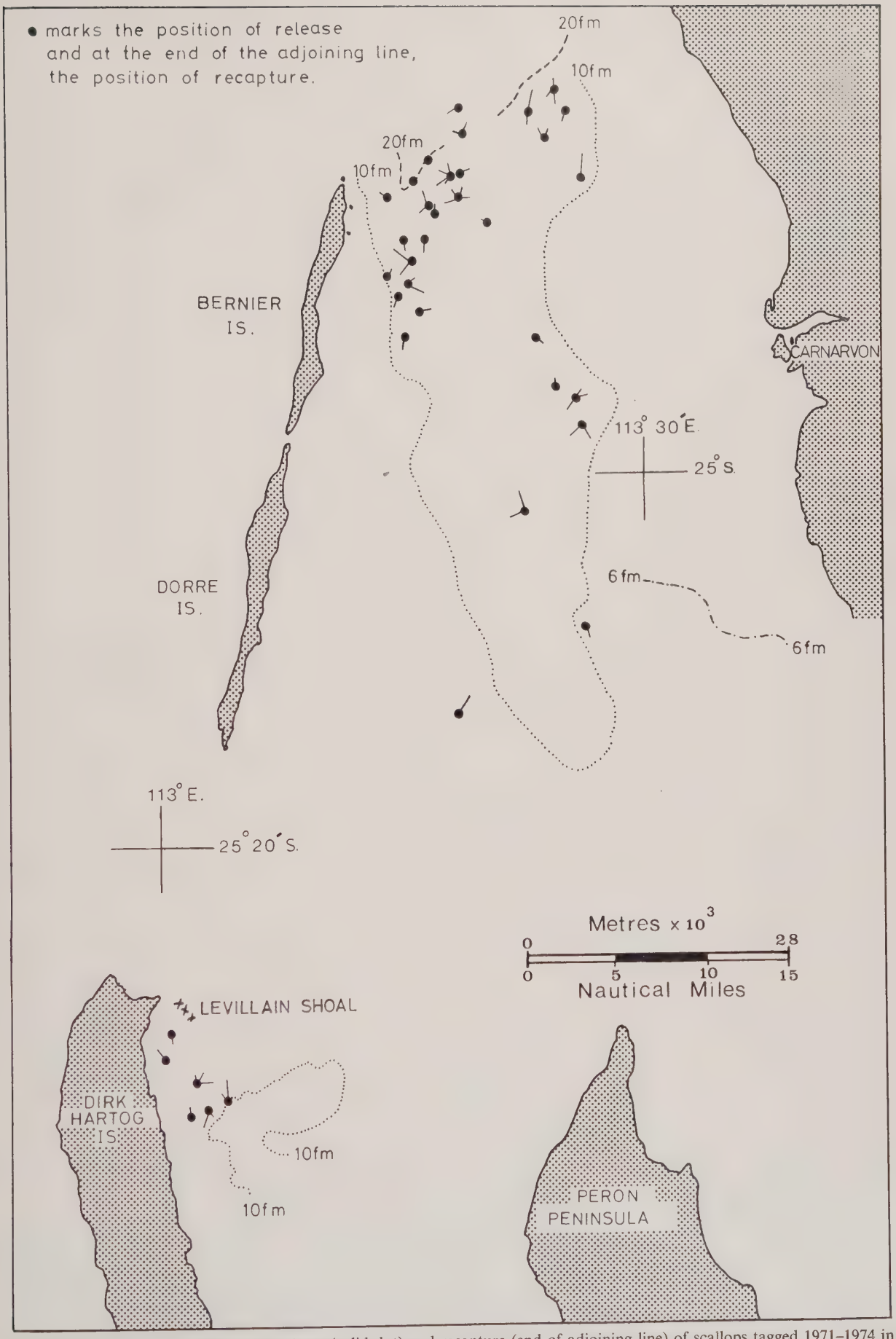

Fig. 15—The radar determined positions of release (solid dot) and recapture (end of adjoining line) of scallops tagged 1971–1974 in Shark Bay, W.A.

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